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Time Domain Analysis of Terahertz Photoconductive Antennas Using High- Frequency Structure Simulator (HFSS)

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Time Domain Analysis of Terahertz Photoconductive Antennas Using High-Frequency Structure Simulator (HFSS)

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by

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Abstract

In this thesis, an in-depth guide and description on how to model and perform frequency and mainly time domain analysis of a THz photoconductive antenna using HFSS will be presented. The main purpose of this thesis is to master and document the procedures for transient domain analysis in HFSS to fill the lack of documentation about this topic. Moreover, another goal is to compare the results from HFSS with the ones from another program, COMSOL (conducted by a PhD student), in order to validate the correctness of the procedure.

From this thesis, it can be concluded that in order to obtain accurate results in the time domain there are some factors that need to be considered. One of this consideration is the fact that the mesh size in the time domain is much smaller than in the frequency domain and must be increased by using some mesh fixing techniques. Another consideration is the fact that while materials properties in the frequency domain can remain constant over a frequency range, in the time domain they automatically follow the Debye model but can be configured differently. Taken into account these considerations, the average electric field in the y-direction inside the substrate of an antenna with custom current source excitation was obtained and compared with the results from COMSOL. Since both results were identical, the procedures developed using HFSS to perform time domain analysis were validated, making this project a success.

Acknowledgments

I would like to express my sincere gratitude to Dr. Magda El-Shenawee for the opportunity to work on this project. Moreover, I would like to thank Nathan Burford for his constant guidance and motivation. Finally, I would like to extend my thanks to Tyler Bowman and Alec Walter for their contribution during group meetings.

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I. Introduction

A. Background and Motivation

ANSYS High Frequency Structure Simulator (HFSS) is a commercial electromagnetic field simulation program developed by ANSYS which uses the finite element method (FEM) in order to solve electromagnetics problems [1]. Using HFSS, one can easily and reliably extract the scattering and impedance parameters, the electric fields in 3-D and much more [1]. This program is usually used to design, analyze, and simulate antennas and other radio-frequency circuits in the frequency domain [1]. In additional to the frequency domain solver, HFSS also has a time domain solver using the FEM [1]. However, although there is a lot of documentation on how to use the frequency domain solver, there is not enough information on how to properly use the time domain solver. One of the reason for this lack of interest might be because there are programs like CST Microwave Studio whose main focus is the time domain solver using the finite integral technique (FIT) and could be more suitable for transient analysis [2]. Nevertheless, since HFSS still have a time domain solver and its license might be more accessible for some people, which is the case at the University of Arkansas, it would be beneficial to develop a guide on how to perform transient simulations in HFSS and to understand what are some of the factors that needs to be considered while performing this type of simulation. Another motivation for this thesis was that during the experiment, one of Dr. El-Shenawee's PhD students, Nathan Burford, was performing a time domain model of a THz photoconductive antenna with a custom current source for his PhD dissertation using COMSOL [3-5]. Thus, having an additional model in HFSS could validate the results from COMSOL, and vice versa.

B. Organization of the Thesis

The rest of this thesis will be organized as follow: Chapter II focus on the steps needed to perform a frequency and time domain analysis of a THz photoconductive antenna in HFSS. In this chapter, an antenna taken from an academic source will be simulated to properly develop the transient analysis method. Chapter III uses the information developed in Chapter II to analyze the THz photoconductive antenna, developed in the group, in the frequency and time domain Moreover, this chapter discusses how to obtain the electric field inside the substrate of the antenna in the time domain in order to compare it with the results from COMSOL. Finally, Chapter IV concludes the thesis.

II. Photoconductive antenna

A. Introduction

In this paper, two different photoconductive antennas will be modeled and analyzed. This type of antennas is the most frequently used for Terahertz generation and detection [6]. Moreover, they are usually comprised of three parts: a laser excitation, the antenna built over a substrate like GaAs, and a bias pad [6]. The final outcome of this experiment and thesis is to model a photoconductive antenna to determine its time domain response to a custom current source excitation. Thus, it is important to ensure that the building block of this process, which is how to model a terahertz photoconductive antenna in HFSS, is performed correctly. In order to accomplish this goal, an academic paper which provides the frequency domain results for the resistance and reactance of a photoconductive antenna was replicated. By replicating the results from the academic paper and by understanding the shortcomings of the process, the validity of future results will be ensured.

An in-depth guide on how to model the photoconductive antenna from the academic paper in HFSS will be discussed in section B. Then, the method to obtain the frequency domain results for the resistance and reactance, and the S11 parameters of the modeled antenna will be explored in section C. Finally, the process to perform the time domain analysis of the modeled antenna and the necessary measures to ensure correct results through mesh fixing methods will be discussed in section D.

B. Modeling the Antenna in HFSS

As stated before, the first step towards the final goal of this thesis is to successfully model a photoconductive antenna. In order to perform all the models and simulations, the software ANSYS Electronic Desktop 2015.2 was used [1]. In addition, the shape, and results for the impedance of the photoconductive antenna which was initially modeled was obtained from the paper by Christopher W Berry et al [7]. The shape of the antenna can be seen in Figure 1.

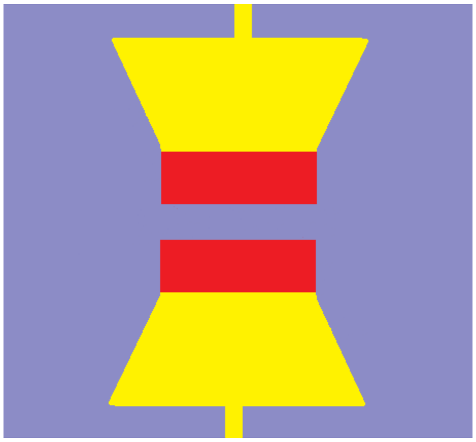

Figure II.1: Shape of First Photoconductive Antenna from Paper [7]

Despite having information about the shape of the antenna and the expected results for the resistance and reactance, the paper fails to provide the dimensions of each individual element of the antenna and the kind of excitation used to simulate the laser inputs. Fortunately, one of Dr. El-Shenawee's previous undergraduate students, Alexis Bell, had previously researched the optimal dimensions of the antenna and excitation model to obtain the closest results to the data published in the paper. The provided shape and the dimensions of the photoconductive antenna can be seen in the Figure 2.

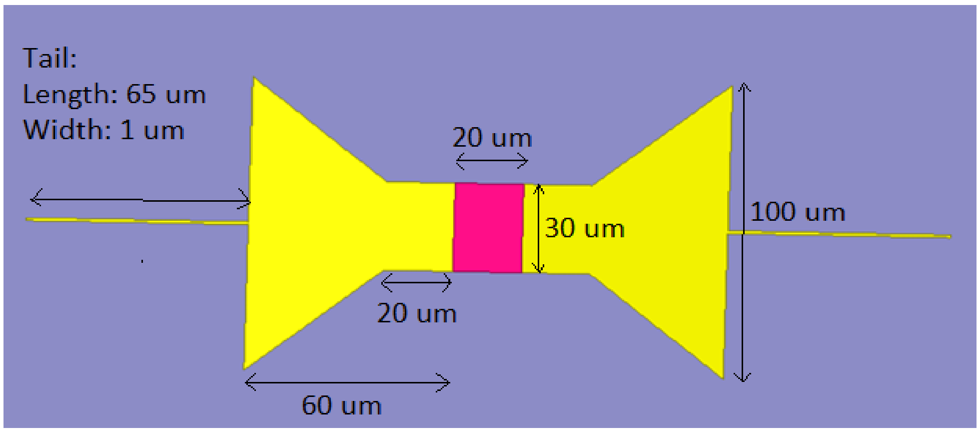

Figure II.2: Dimensions of the Photoconductive Antenna [7]

After knowing the actual dimensions of the photoconductive antenna, the process to start modeling in HFSS can begin. The first step is to launch ANSYS Electronic Desktop software. Once it has been opened, a new project must be created from the file tab in the top left menu. A project must have appeared in the project manager in the left. The next step is to right click this project and select insert HFSS design in the insert tab. After selecting this option, a new white window, the work area, with the three Cartesian axes will appear in the right. From Figure 2, it can be seen that the units used in the antenna are micrometers but HFSS's default option is millimeters. The units can be changed by selecting the units' option in the Modeler tab. Another useful option to have enable is the ability to edit a newly created object. To enable this option, 3D Modeler option must be select from the Tools tab and the Options subtab. Then, in the drawing tab, the last option which edits properties of new primitives must be selected. Once the initial configuration has been taken care of, the actual model of the antenna can be constructed. The first step is to insert the substrate by selecting the box option in the Draw tab. Then, left click three times to make the shape of box in the work area. A new window like the one shown in Figure 3 will open.

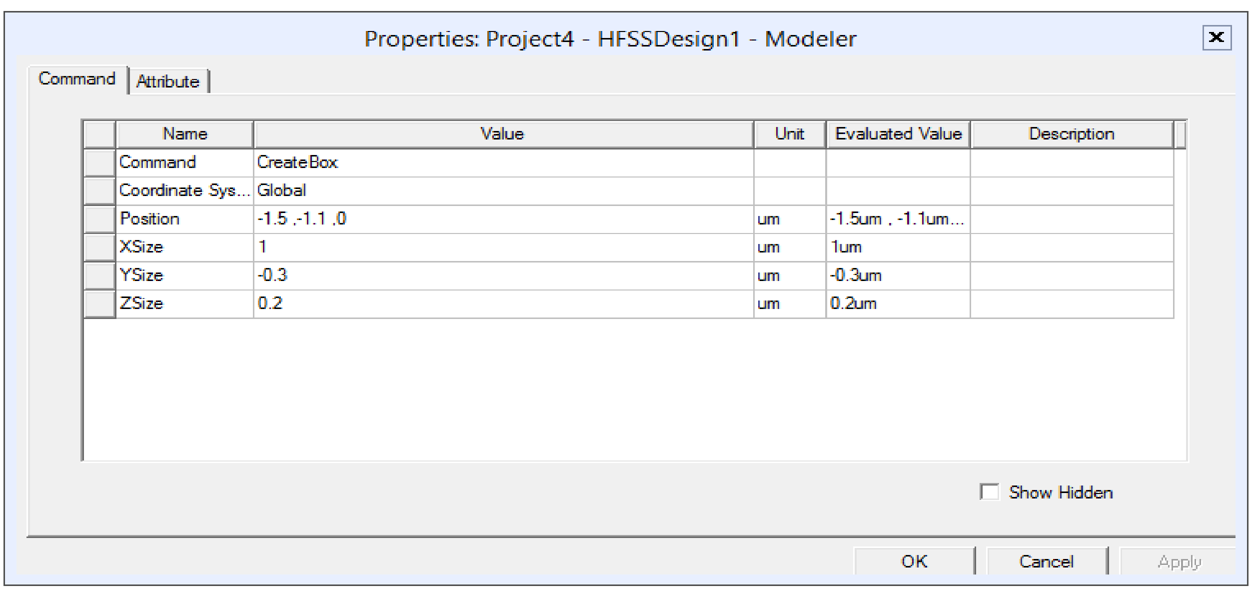

Figure II.3: Properties of newly created object

In this new window there are two important tabs: the Command and the Attribute tab. The first one allow to change the dimension and position of the object. In the case of the substrate, the position is -350 um, -350 um, 0 um, and the dimensions are 700 um, 700 um and -500 um in X, Y and Z, respectively [7]. The second option allow to change the name, color and more importantly the material type of the object. In this case, the material for the substrate is Gallium Arsenide (GaAs). To change the material from vacuum (default in HFSS) to GaAs, left click on vacuum and select edit. This action will pull up a list of different materials store in HFSS. To add the custom GaAs property, click on Add material, give it a custom name, a Relative Permittivity of 12.7, and click OK [7]. After creating the substrate and assigning its properties, the next step is to create the air box on top of the substrate using a similar procedure. To perform this action, a box from the Draw tab need to be selected and placed on the work space. The position of the air box is the same as the substrate but the dimensions are 700 um, 700 um and 300 um [7]. In general, the height of the air box has to be at least a quarter or half of the wavelength [8]. Finally, the material property of the air box is vacuum. The next step on the list is to add the conductive element of the antenna with the dimensions as shown in Figure 2. This element will be modeled using three different parts: left wing, right wing and the excitation part in the middle.

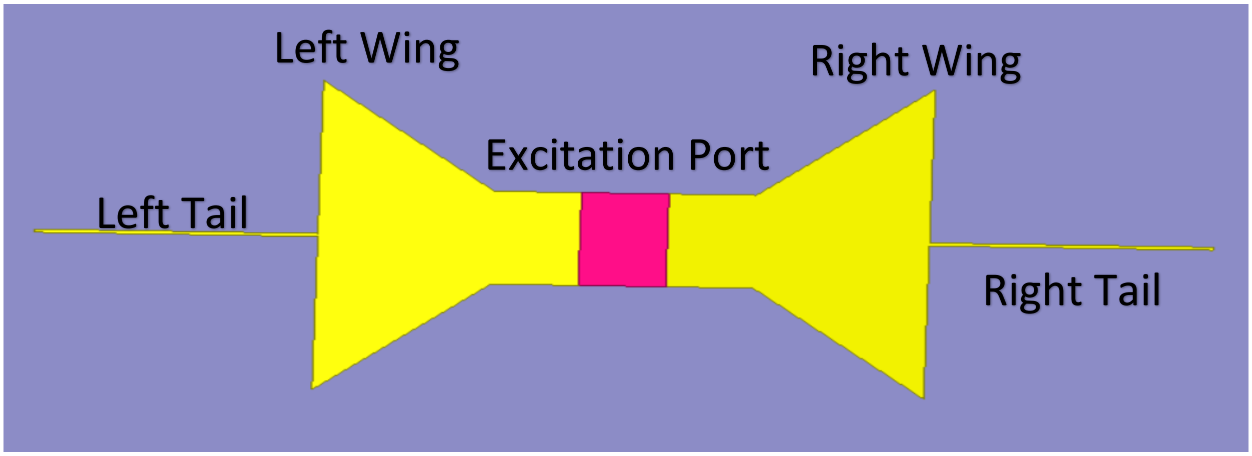

Figure II.4: Conducting element of the antenna

In order to design the left wing, a rectangle should be selected from the Draw tab and added on the work space. The position of the rectangle should be 10 um, -50 um, 0 um and with a dimension of 60 um, and 100 um in X and Y, respectively [7]. In order to create the triangular shape, as seen in Figure 4, from the square, the line option from the Draw tab will be used. A triangular shape with the dimensions that will be removed from the square needs to be created using the line option in the top and bottom. Once both objects have been created, hold control on the keyboard and select the bottom and top object created by the line option and the square. After selecting those three objects, right click and the subtract option in the edit tab and Boolean subtab. Make sure that the rectangle is in the blank or left side and the other two objects are in the tools or right side. By doing this, the shape of the two objects will be deleted from the main rectangle, giving it the form shown in Figure 4. Then, the left tail can be included in a similar fashion by adding another rectangle with position, 70 um, -0.5 um, 0 um and dimension 65 um, and 1 um [7]. In this case, instead of using the subtract option in the Boolean subtab, the Unite option in the same subtab will be used. After this process, the left wing has been modeled with the same dimension and shape as in Figure 2. The same procedure must be repeated in order to obtain the right-wing portion of the antenna. The final step is to create the excitation port in the center of the two wings. To do so, create a rectangle with position -10 um, -15 um, 0 um, and dimensions, 20 um and 30 um [7]. Now, all the elements of the photoconductive antenna have been added to the design.

C. Assigning Excitation, Boundaries, and Frequency Domain Solution

After all the elements of the antenna have been added to the design, the next step involves assigning the excitations and boundaries. In HFSS, the excitation can be approximately simulated by using a lumped port. The reason for using a lumped port excitation is because it allows the extraction of S- parameters inside the boundaries of the design as opposed to the wave port excitation which can only be applied externally [8]. To apply this type of excitation, right click the excitation port in the design and select Lumped port in the excitation tab, as shown in Figure 5.

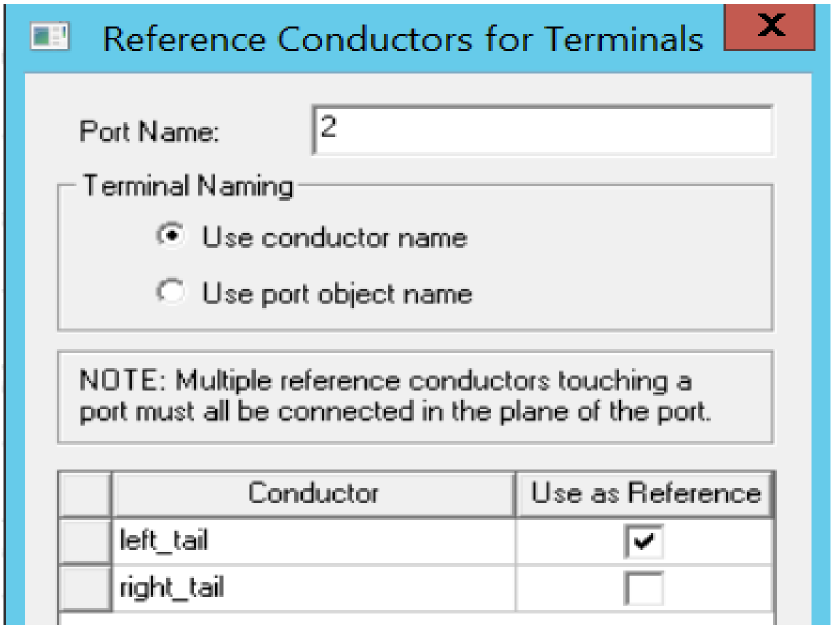

Figure II.5: Excitation Option

Now that the antenna has been assigned a proper excitation, the next step is to assign the boundaries of the antenna. There are two boundaries that need to be applied in this type of antenna: the boundary on the conductive element of the antenna and on the external limits of the antenna. In this design, the conductor for the antenna is gold [7].

Knowing this additional information, a finite conductivity with the properties of gold can be assigned on both wings of the antenna. In this case, the default properties of gold available in HFSS will be implemented. While a perfect electric conductor could also be applied, it would be more accurate to the original design to model the antenna as an imperfect conductor. To assign the boundary on the conductive element of the antenna, hold control on the keyboard and click on both the right and left wing of the antenna. Then, right click and select the Finite Conductivity option in the Assign Boundary tab. A new window will be opened and it must be filled with the information as shown in Figure 6.

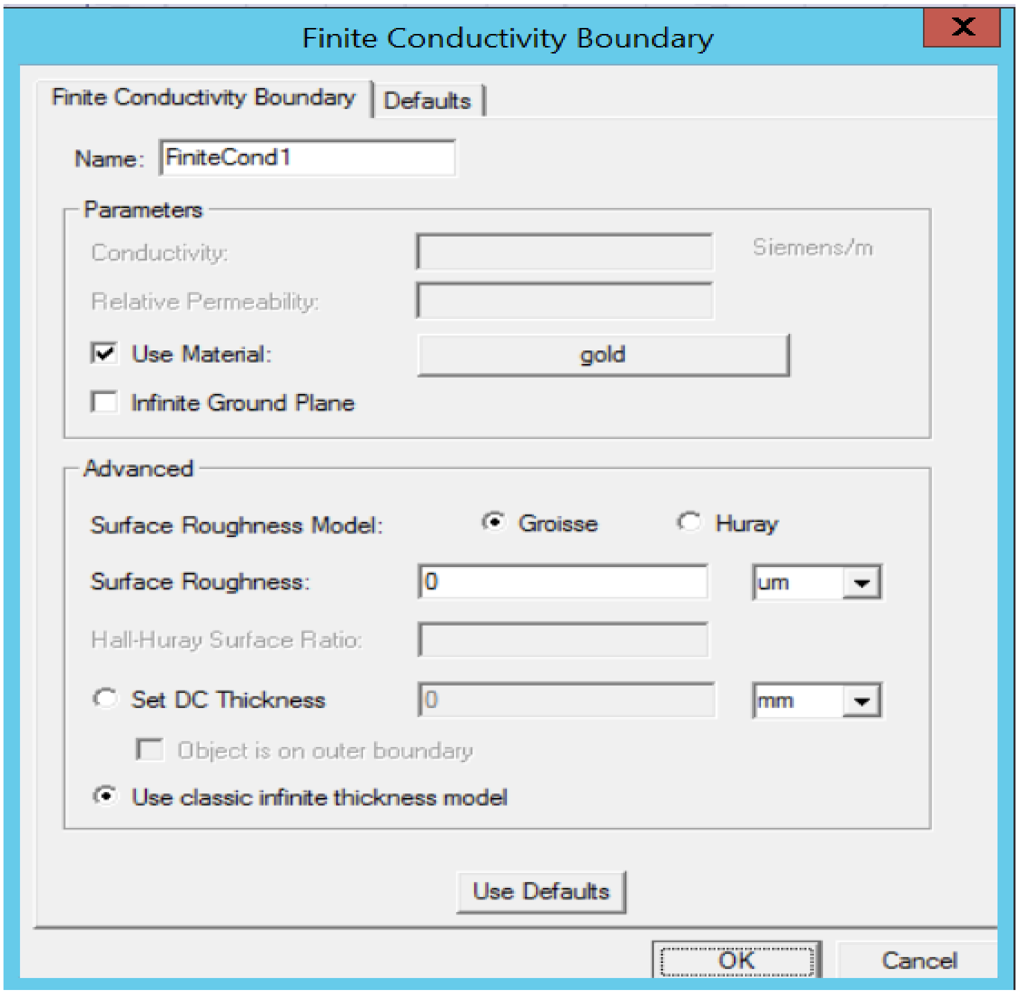

Figure II.6: Boundary Configuration for the Finite Conductivity

The final boundary that needs to be assigned to the designed is the external boundary. The external boundary that will be applied is called Radiation boundary [8]. This boundary simulates an open space like in the case of this antennas and absorbs the waves at the boundary to avoid reflection [8]. This boundary should be applied to all the external faces of the design. In order to assign this final excitation, the F key in the keyboard must be pressed in order indicate HFSS to select faces instead of whole objects. Then, while pressing the control key, select all the external faces of the design, which consist of 10 total faces from the air box and substrate. After selecting the 10 faces, right click on the work space, and select the Radiation option in the Assign boundary tab and click OK when prompted on the new window. Now that the design of the antenna has been made and the proper excitation and boundaries have been assigned, the next step is to perform a frequency domain simulation on the antenna in order to compare with the results given in the literature.

The next step involves setting up the configuration of the analysis and the frequency sweep. To create a new analysis, right click the analysis option in the project manager and select add solution. This will let the user assign the solution frequency which the solver will continue to iterate until it gets a convergence [8]. In this case, the solution frequency will be set to 425 GHz. Moreover, the number of passes or number of iterations will be set to 20 and the maximum delta S, which is the maximum difference between two iterations, will be set to 0.005.

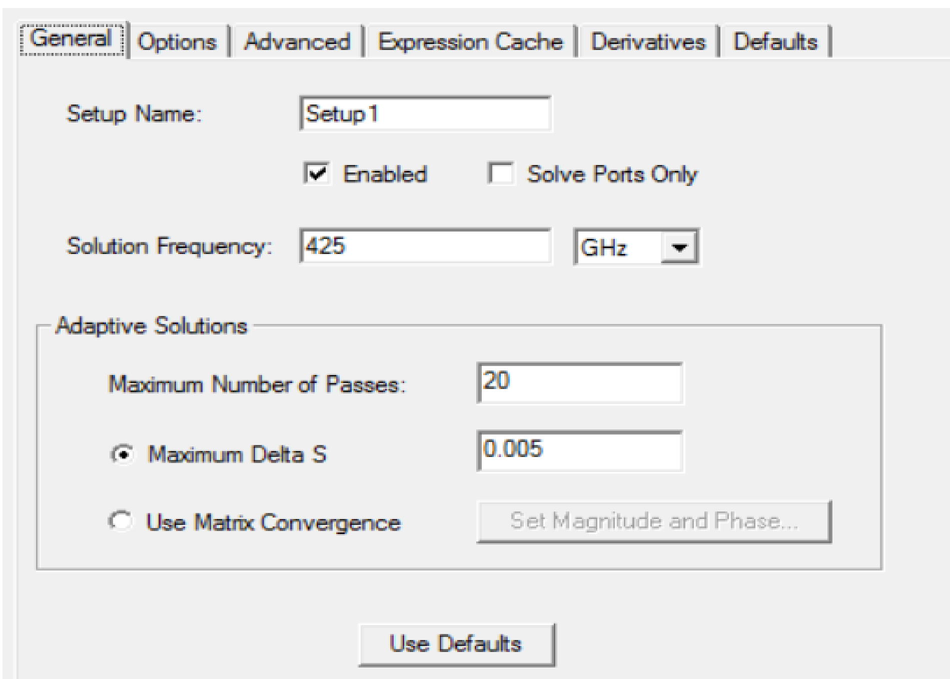

Figure II.7: Adding a Solution Option

With the current configuration, HFSS will only simulate and solve the design at the solution frequency. However, one would expect to get the response of the antenna over a wider range of frequencies. To accomplish this, a frequency sweep must be included in the solution analysis[8].

To perform such operation, right click on Setup 1 under Analysis and select Add Frequency Sweep. The Sweep will be performed from 100 GHz to 1500 GHz since this is the frequency range given in the solution from the academic paper. Moreover, since the initial and final frequency are far from each other interpolating frequency sweep should be performed [8]. If this were not the case, a fast frequency sweep could be performed to increase the speed of the simulation [8].

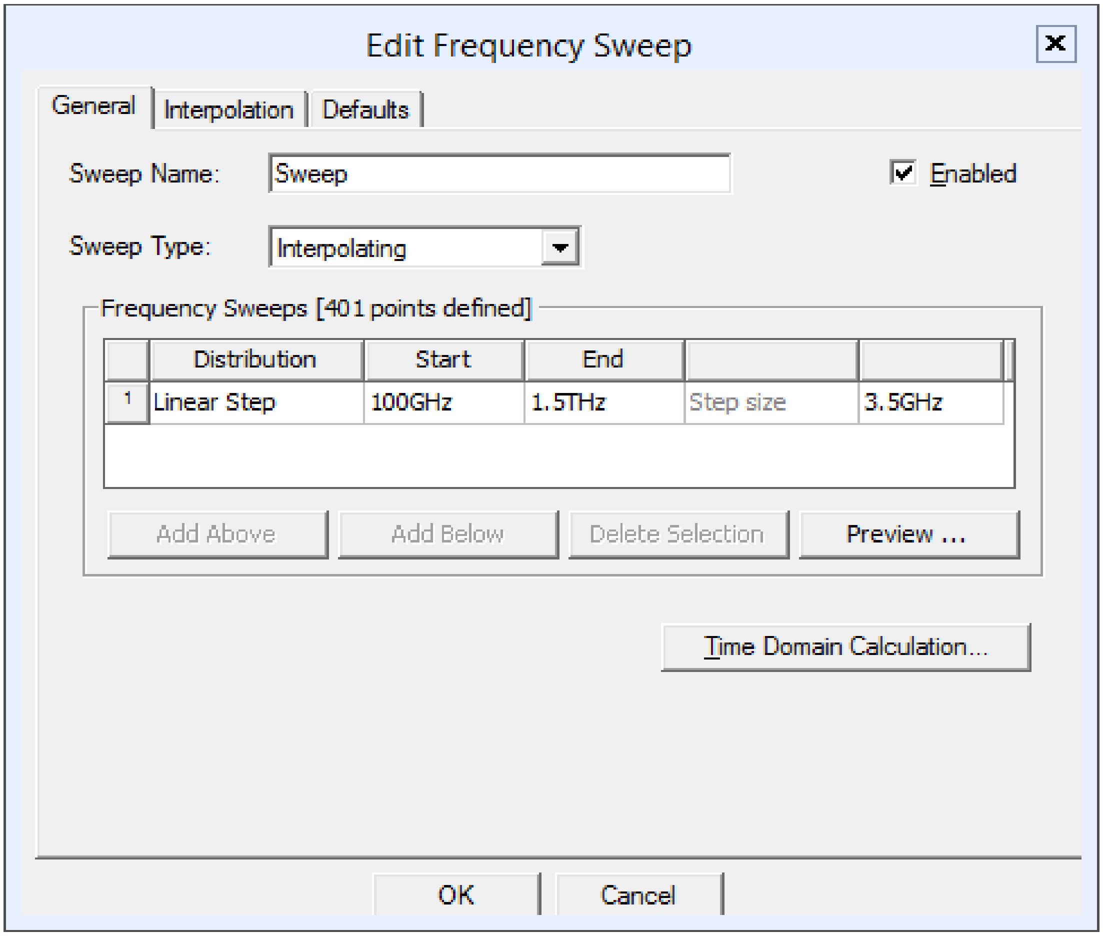

Figure II.8: Sweep Settings

Before performing the analysis, it is important to check that all the configurations and the design have been generated correctly. To do this, select the Validation Check option under the HFSS tab. If everything was done correctly, a window like the one in Figure 9 will show up with green marks. However, if there is an error somewhere, it will show a red cross and the problem will be stated in the message manager at the bottom.

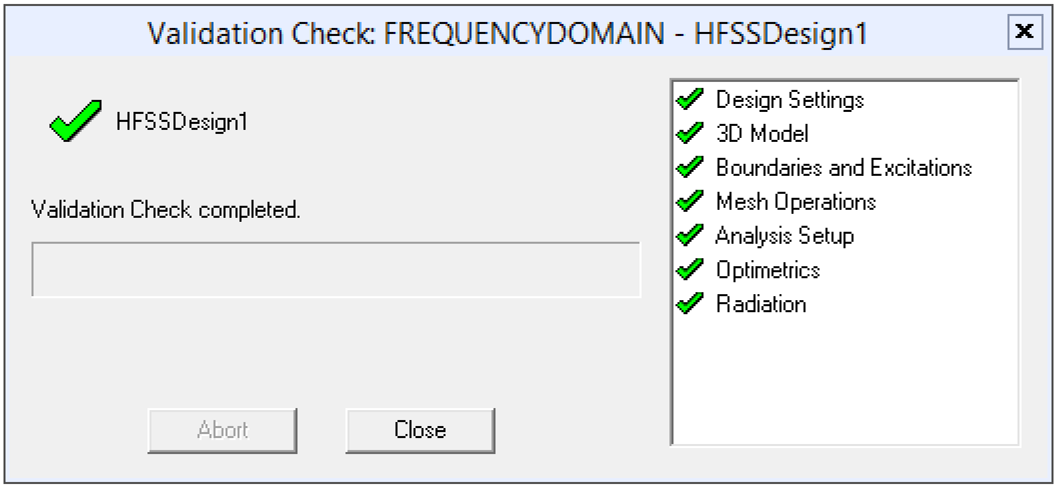

Figure II.9: Validation Check

Now that all the configurations and settings have finally been taken into consideration, the design can finally be analyzed by HFSS to obtain the frequency domain response of the antenna over the assigned frequency range. In order to perform the analysis, the analysis all option under the HFSS tab must be selected. After doing this, HFSS will start the iterative analysis of the antenna. This process can take from some minutes to a couple of hours depending on the machine and type of license possessed. When the analysis is completed, the frequency domain response of the antenna becomes available. In order see the results, right click on the Results in the project manager and select Rectangular Plot from the Create Terminal Solution Data Report tab. From the newly opened window, the results for the S11 parameters, the Z parameters, the Y parameters can be selected. In the academic paper, the Z parameters are the only information provided and will be compared against the results in this project. To show the Z parameters from the recently solved antenna in HFSS, the Terminal Z Parameter option must be selected under category and both imaginary and real options must be selected under function. A comparison of the results from the simulation in HFSS and from the academic paper can be seen in Figure 10. In addition, the S11 parameter can be generated with the same process, and are shown in Figure 11.

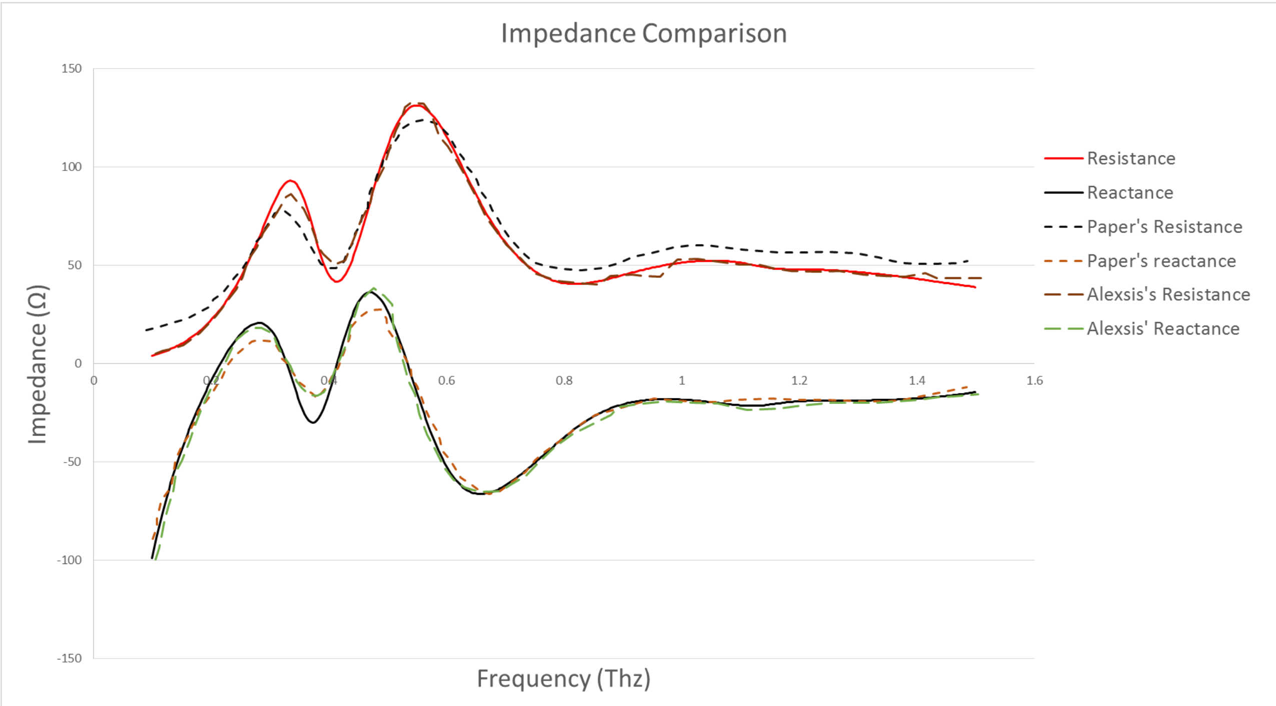

Figure II.10: Impedance Comparison [7]

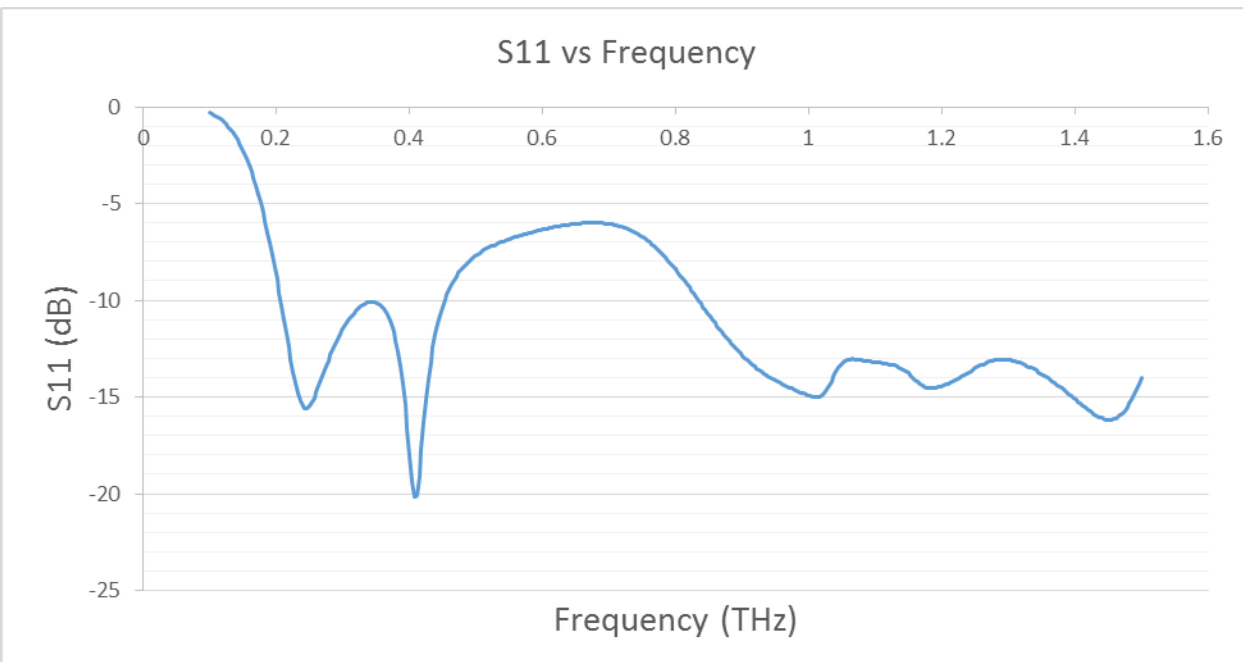

Figure II.11: S11 Parameters for Photoconductive antenna in academic Paper

From Figure 10, it can be seen that the results from the academic paper and from the simulation in HFSS are in good agreement. The main source of error comes from the fact that the author of the paper did not provide documentation on how the port of the antenna was simulated and its dimensions had to be experimentally chosen to obtain the closest result to the paper. Considering this issue, the results obtained from the simulation are within expected deviation from the results in the paper. Since the results from the simulation were like the ones in the paper, it can be concluded that the model and analysis of the Terahertz photoconductive antenna in the frequency domain using HFSS was successful.

D. Time Domain Response and Mesh Fixing Methods

Having mastered the right configuration to model a photoconductive antenna in HFSS, the logical step towards the end goal of this thesis is to perform a time domain analysis of the antenna instead of a frequency domain analysis as it was discussed in Section C. The current configuration of the project, Driven Terminal, only allows frequency domain analysis of an antenna [8]. In order, to examine the time response the solution type of the project must be changed to Transient [8]. In order to do so, right clicked the HFSSDesing1 option in the project management and select Solution Type. Then, instead of Driven Terminal select the Transient option as seen in Figure 12.

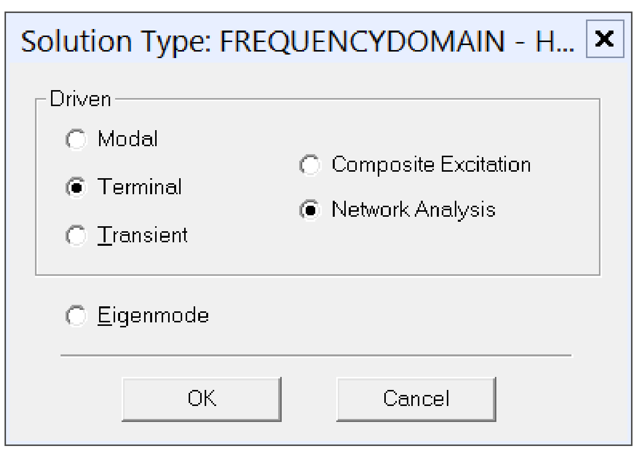

Figure II.12: Solution Type

After doing this, it can be seen that the antenna design in the work space, the boundaries and the excitation remained the same, but the Analysis options that were added previously disappeared from the Project Manager. By right clicking on the Analysis tab and selecting Add a Solution Setup a new window that will be used to set up the configuration in the time domain will be opened as seen in Figure 13.

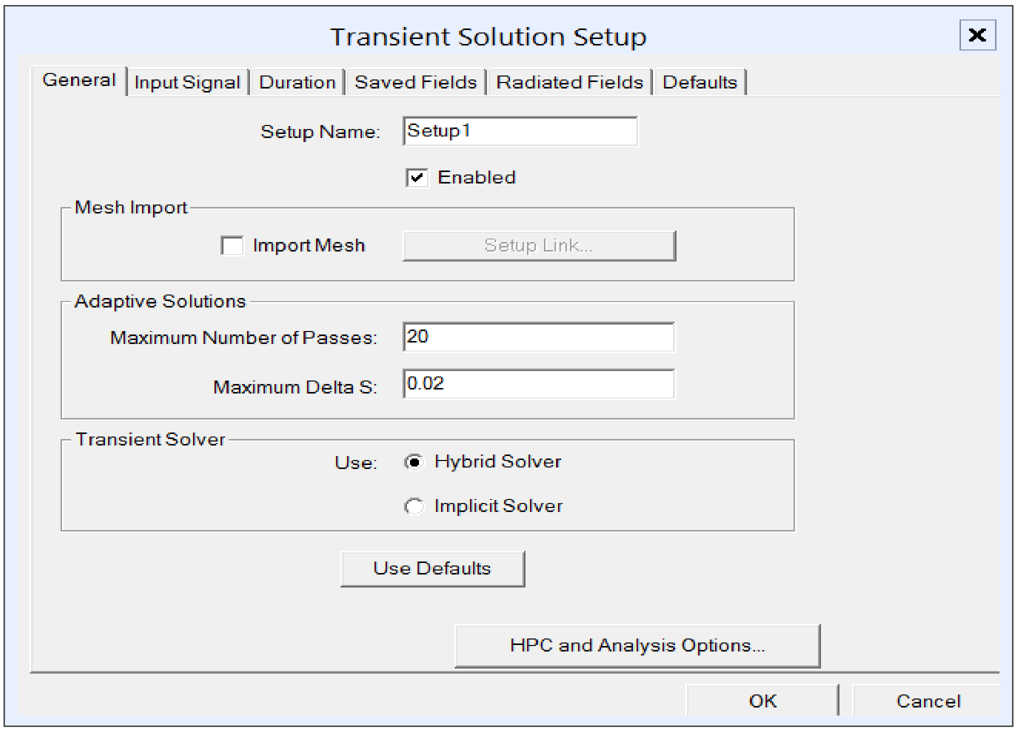

Figure II.13: Transient Analysis General

The first configuration from Figure 13, allows the user to determine the number of passes or iterations and the maximum Delta S or difference between iterations. In addition, it let the user import a Mesh, a process which will be discussed later in this section, and pick a Transient Solver; in this case the Hybrid Solver yielded the more consistent results and will be the one used through the project. The other important setting that will be used in this section are in the Input Signal Tab. The settings from this tab can be seen in Figure 14.

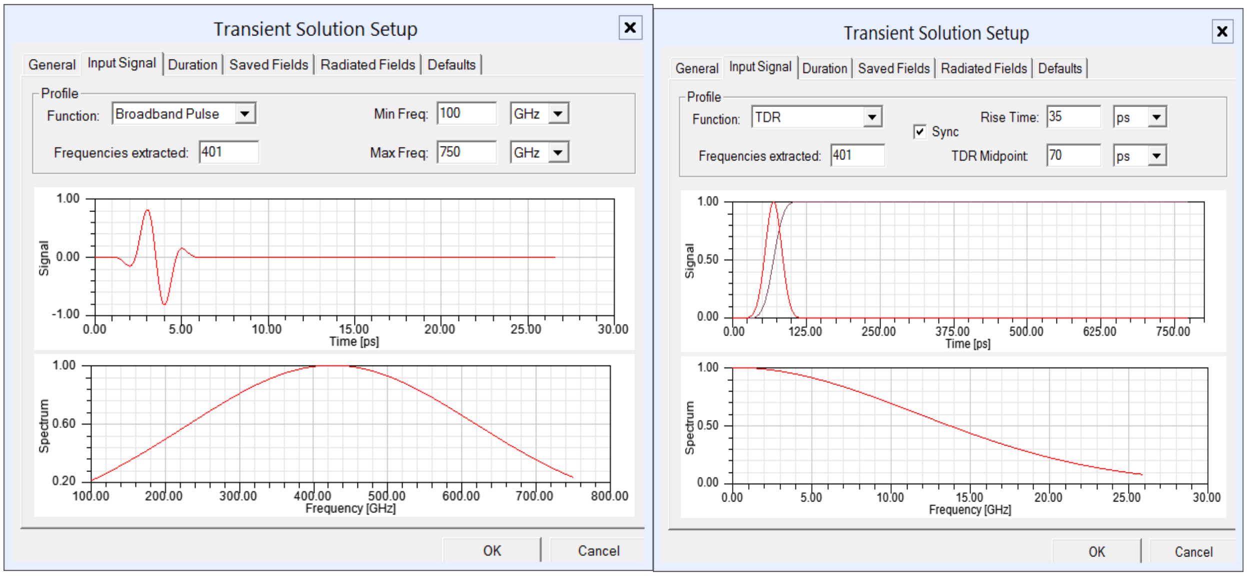

Figure II.14: Transient Analysis Input Signal

The settings from the input tab let the user determine the input signal that will be fed to the excitation port in order to obtain a response from the antenna [8]. Unlike the frequency domain, in the time domain analysis the solution frequency cannot be picked directly. The solution frequency in this setting will be picked according to the type of input used and the range of the input [8]. There are two types of signals allowed in this mode: a Broadband Pulse and a TDR pulse. In the first case, the user can pick the frequency range of the excitation and the solution frequency will be the point where the Gaussian in the frequency Spectrum reach its maximum [8]. Conversely, the TDR pulse is a Gaussian in the time domain and the center frequency from the frequency domain spectrum will be used as the solution frequency [8]. From this, it can be seen that the only way of picking a solution frequency is by changing the range of the frequency in the Broadband pulse and changing the Rise time and TDR Midpoint in the TDR pulse. Since the solution frequency for the antenna is 425 GHz, a broadband pulse with Min frequency 100 GHz and Max Frequency 750 GHz should be used. Initially, this information was not known. Thus, a frequency range from 0.1 THz to 1.5 THz was initially chosen, which make the solution frequency higher than what it should be. The solution frequency can be verified by double clicking the Analysis tab in the project manager. After selecting the necessary configurations, a validation Check must be performed and the simulations analysis can be performed.

Once the simulation has ended, right click Results and select Rectangular plot from the Create Terminal Solution Data Report tab. Because the input port was a lumped port, there are two types of results that can be displayed: spectral (frequency) and transient (time) [8]. Any of these two results can be picked from Solution option in the context tab. In order to compare the results from the type domain response to frequency domain response and the results from the paper, the spectral results for the Z parameters and the S11 parameters will be displayed. The comparison for the Z parameters can be seen in figure 15 and for the S11 parameters can be seen in Figure 16.

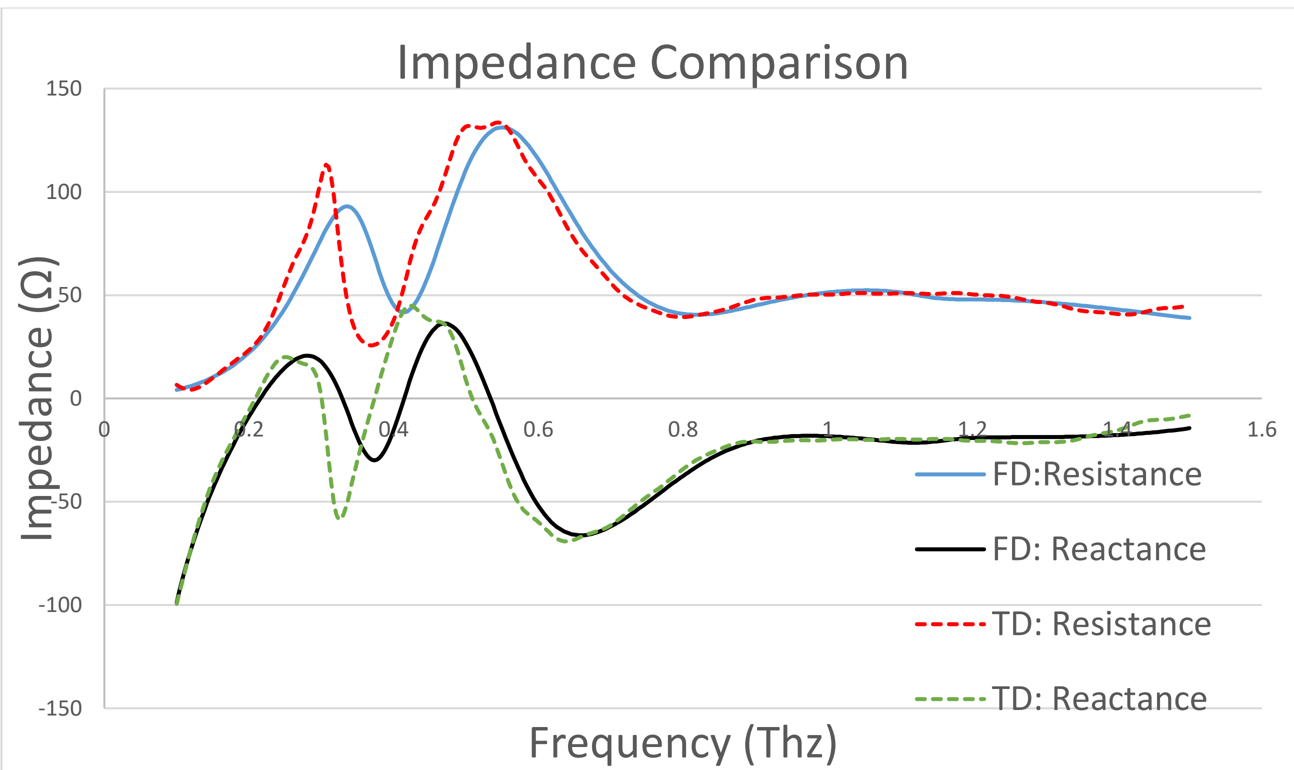

Figure II.15: Z Parameters Time domain

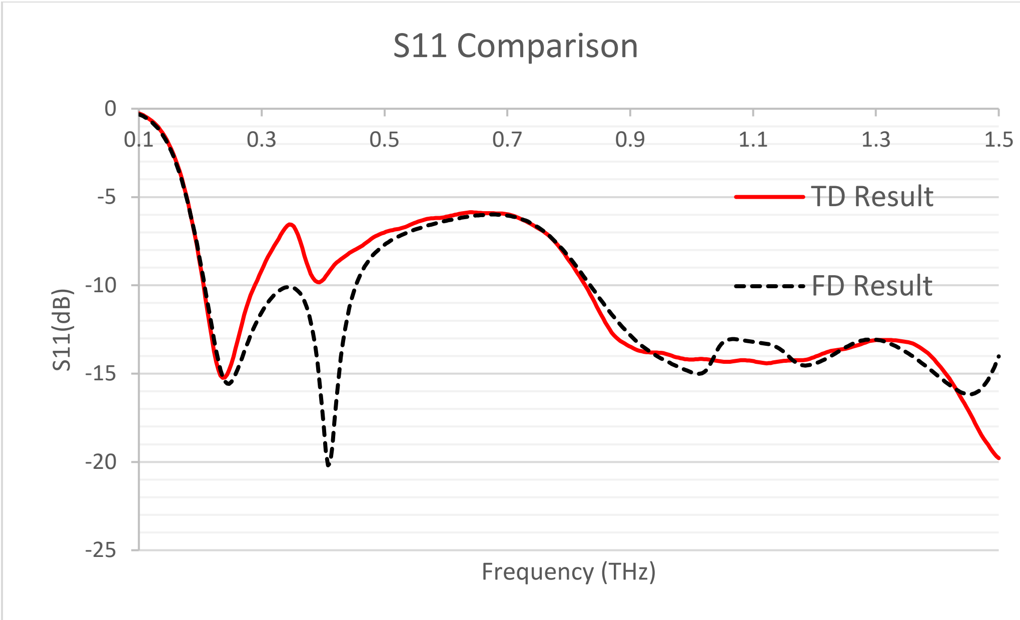

Figure II.16: S11 Parameters Time Domain

From the graph, it can be seen that although the solution for the Z parameters were somewhat closer to the actual results, the S11 parameters differ greatly at lower frequencies. The reason for this behavior is that solution frequency was automatically set to 800 GHz because the range of the Broadband pulse was set from 0.1 THz to 1.5 THz. That is why in the results from Figure 15 and Figure 16, the results are the same around this frequency. Thus, in order to choose the proper solution frequency, the range of the broadband pulse must be change to a minimum frequency of 100 GHz and a maximum Frequency of 750 GHz. However, when the solution frequency was changed, the results did not improve as one would have expected. Thus, there must be another issue that was not considered. After many experiments, it was noticed that the mesh size for the frequency domain analysis was much larger than in the time domain analysis. The main reason for this difference in the mesh size is that the frequency domain solver has a lambda refinement process which refine the mesh [8]. This option greatly increases the size of the mesh in the frequency domain and is not available in the time domain analysis [8]. From this knowledge, increasing the mesh size could solve the discrepancy in results.

There are three ways to increase the mesh size in the Transient solution: by importing a mesh from the frequency domain, by making the percentage of convergence small, and by changing the solution frequency multiple times and repeat the analysis. In order to import a mesh a project which was solved using the correct solution frequency in the frequency domain must be stored somewhere in the computer. Then, in the general tab of the Transient analysis, Figure 13, the import mesh option must be selected. By doing this, the window shown in Figure 17 will be displayed. After that, click on the three-dotted box to find the project where the antenna in the frequency domain was solved. Finally, click on the Variable Mapping tab and select Map Variable by name. After doing this, the mesh from the other project will have been imported.

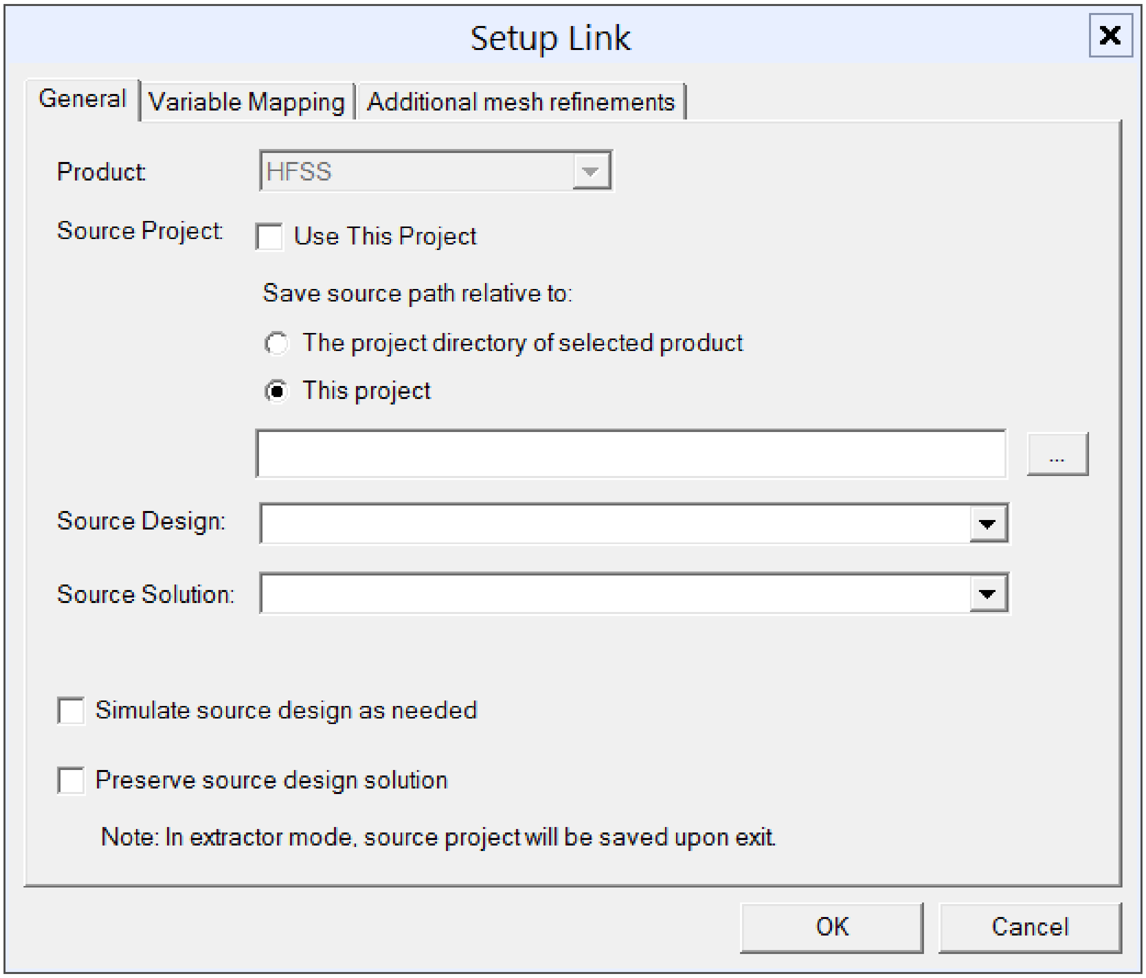

Figure II.17: Importing a Mesh

The next method to increase the mesh size is to reduce the percentage of convergence in the general tab of the Transient analysis, Figure 13. By doing this process, HFSS is forced to do more iterations in order to get the value of delta S that was assigned. Moreover, each time HFSS performs a new iteration the size of the mesh is increased. Thus, with a value small enough for the percentage of convergence, the size of the mesh will increase closer to the one in the frequency domain. The final method to increase the mesh size is to pick a solution frequency and run an analysis. Then, pick another solution frequency, and re-run the analysis. By doing this, HFSS reuses the previous solution and mesh in order to solve the new solution frequency. Thus, the size of the mesh is increased each time a simulation is executed with a new solution frequency. After performing all these operations, the new results can be seen in Figure 18.

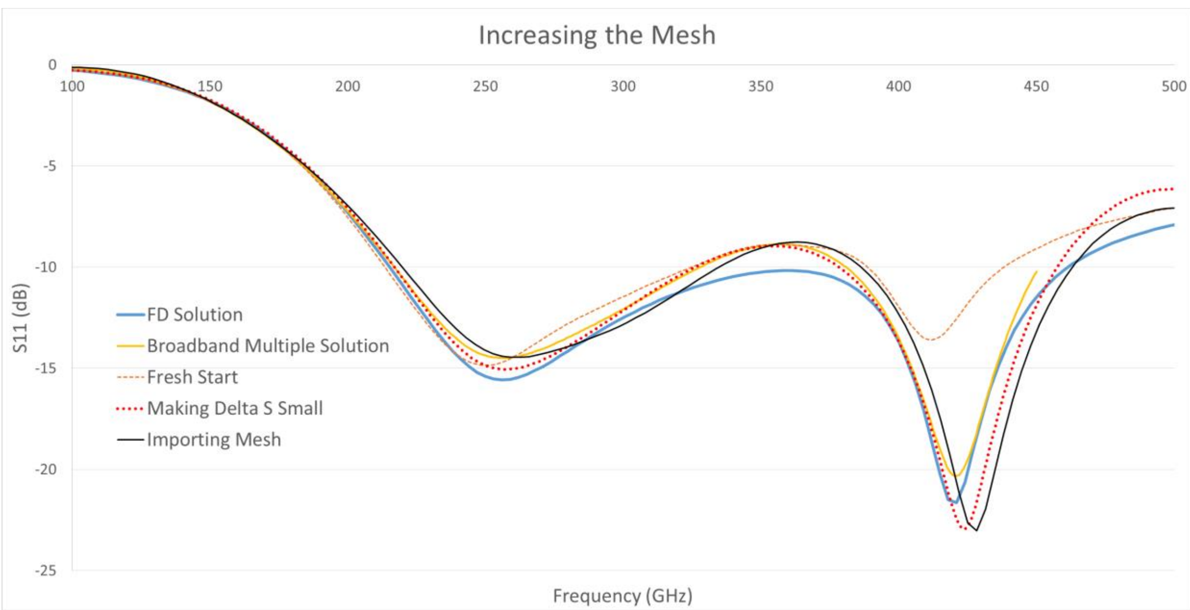

Figure II.18: Mesh Fixing Methods

Comparing Figure 16 from Figure 18, it can be seen that the mesh fixing methods improved the accuracy of the results. Using the mesh fixing methods, the results from the time and the frequency domain are more similar near the solution frequency. Although there are some small differences, it will be shown in the next chapter that some minor difference in the frequency domain does not have a huge impact in the time domain. Now that the proper settings to perform time domain analysis have been understood and mastered, the next step is to apply those settings on the THz Photoconductive antenna.

III. THz Photoconductive Antenna

A. Introduction

In the previous chapter, the process on how to perform a transient analysis on the antenna from the academic paper was developed. The process, however, was limited to only finding the S and Z parameters. In the case of THz photoconductive antenna, a custom current source is used to excite the port of the antenna and the parameter of interest is the average electric field in the y-direction inside the semiconductor GaAs substrate. Thus, the process on how to import and apply a custom current source and how to obtain the average electric somewhere inside the substrate must be developed.

In this chapter, the THz photoconductive antenna, designed by the PhD student Nathan Burford, will be modeled in HFSS [3-5]. The frequency and time domain responses of the antenna, which was discussed in Chapter II, will be presented in section B. Then, some additional parameters that needs to be taken into consideration like the materials properties of the dielectrics and the reduction of the size of the antenna will be discussed in section C. In addition, the process to import a custom current source signal to excite the port of the antenna and the process to calculate the average electric field in a substrate will be discussed in section D. Finally, the results for the average electric field in the y-direction of the antenna in COMSOL, conducted by Nathan Burford, will be compared to the results from HFSS in section D, as well.

B. Modeling and Simulating THz PCA in HFSS

Since the THz photoconductive antenna (PCA), designed by Nathan Burford, and the antenna used in the previous chapter have different shapes and dimensions, a new project must be created to model the new antenna. Once the previous project had been closed, create a new

HFSS project with the Driven Terminal solution type. As in the previous chapter, the following step is to use boxes to create the air box and substrate, and rectangles to make the conductive element of the antenna. As before, the material for the substrate is semiconductor, GaAs, and for the air box vacuum. The dimensions of the GaAs substrate are 700 um, 700 um, and -500 um while the dimensions for the air box are 700um, 700 um, 300 um [3-5]. The shape and dimensions of THz PCA can be seen in Figure 1.

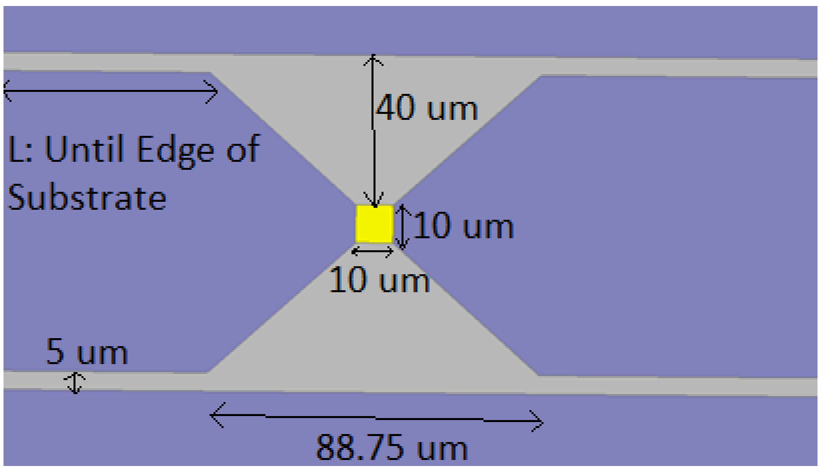

Figure III.1: Assign the Dimensions [3-5]

Using the dimensions and shape of the antenna from Figure 1, the antenna can be easily modeled using the same procedure discussed in section B of Chapter II. Each wing of the antenna can be made by initially making a rectangle and then using the line and Boolean option to give it its triangular shape. Moreover, the excitation port can be made by making a rectangle with dimensions 10 µm by 10 µm between the two wings of the antenna [3-5]. After the new antenna, has been modeled, the next step is to provide the excitations and boundaries. As before, the excitation assigned to the port in the center of the antenna is a lumped port excitation. In the case of the boundaries, all the exterior faces of the air box and the substrate are assigned radiation boundaries while the two wings of the antenna are assigned perfect electric boundary. Then, a new solution setup must be added in the analysis tab. However, unlike the previous antenna, the solution frequency is not yet known for this antenna. Thus, in order to determine the solution frequency, an initial value must be chosen by iteration. This means that an initial value for the solution frequency is selected and from the results of that value a new solution frequency must be chosen. Initially 500 GHz was chosen as the solution frequency, but the results showed that the lowest peak of the S11 occurred around 390 GHz. Thus, 390 GHz was chosen as the new solution frequency and the simulation was performed again. The result for the frequency domain can be seen in Figure 2.

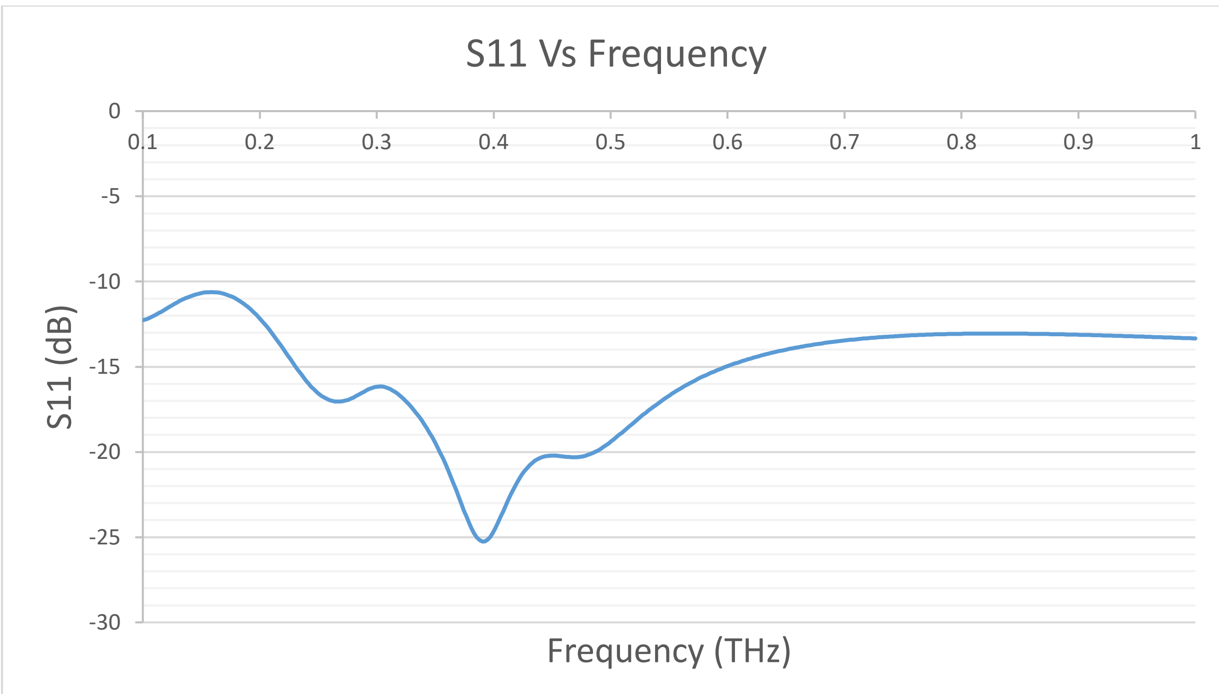

Figure III.2: Frequency Domain Results for the THz PCA

After obtaining the results from the frequency domain, the next step is to perform the time domain analysis of the antenna and compare the results to the frequency domain. In order to do so, the solution type of the project must first be changed from Driven Terminal to Transient. Then, a new solution setup must be added. In the input signal tab, a Broadband pulse will be used with a frequency range from 0.1 THz to 0.68 THz. By using this range, the solution frequency used by HFSS is exactly 390 GHz, which matches the solution frequency used in the frequency domain simulation. After assigning the solution frequency, the following step is to use one of the mesh fixing method discussed in section D of Chapter II. Once any of those methods have been assigned, the simulation analysis can start. After completing the simulation analysis, the spectral result for the S11 must be selected to compare it to the results from the frequency domain. The comparison of the S11 results for the frequency domain and time domain using different mesh fixing method can be seen in Figure 3.

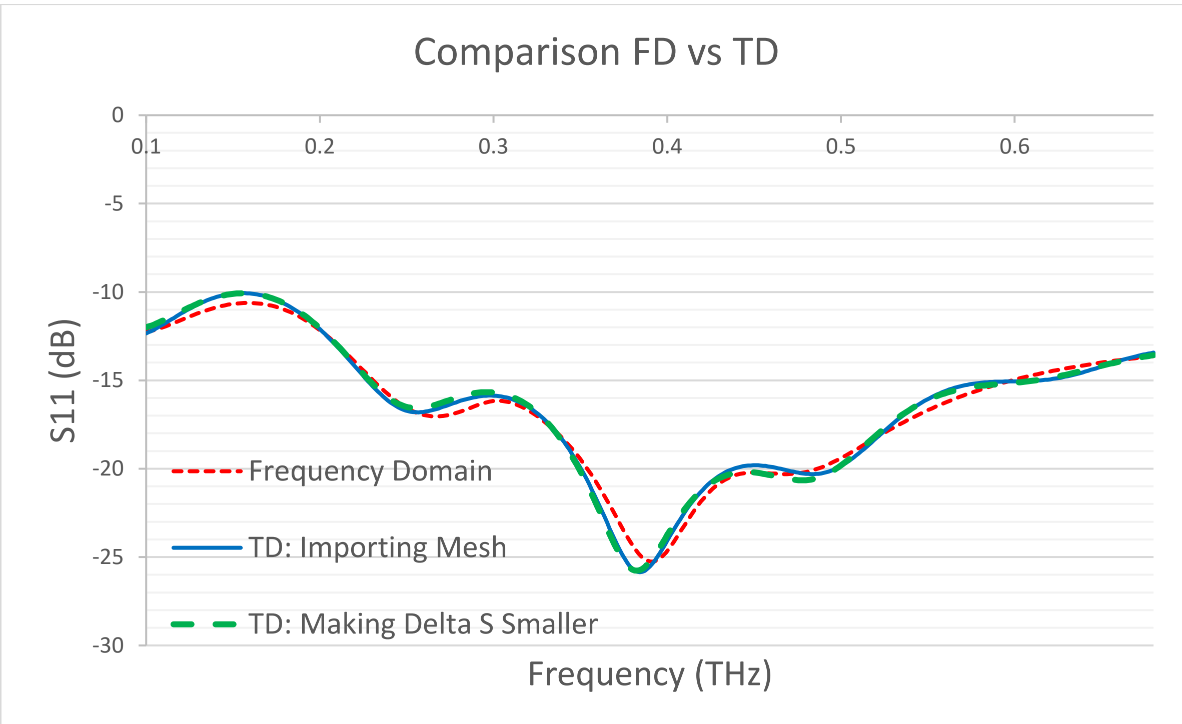

Figure III.3: Comparison between the Frequency and Time Domain of the THz PCA

From Figure 3, it can be seen that there is a good agreement between the results from the frequency and the time domain. One of the reason for the similarity between the results is the fact that the mesh fixing method that were discussed in section D of Chapter II were applied. Before using a custom current source to excite the port of the antenna, there are some considerations that need to be considered in the time domain.

C. Time Domain Considerations and Size Reduction of the Antenna

Before proceeding to the next section, it is important to take into consideration some factors that could have an impact on the results of the antenna. One of the major factors are material properties [8]. In the frequency domain solver, the permittivity of the dielectric is assigned to be constant over the frequency range of the simulation [8]. However, in the time domain solver, the permittivity of the dielectric needs to have a frequency dependency to satisfy causality [8]. To fulfil this requirement, HFSS solver automatically uses the Debye model [8]. However, if one knows exactly the how the permittivity of the dielectric changes with respect to frequency, that information can be inputted into HFSS to obtain more accurate results.

In order to verify the effect of this frequency dependence on the results of the antenna, the material properties for the Gallium Arsenide will be modified to a version of the Debye model using a custom input, and to a version using a custom formula [9]. In order to change the material properties of the GaAs substrate in the model to a Debye model with custom input, right click on the substrate and select properties as seen in Figure 4.

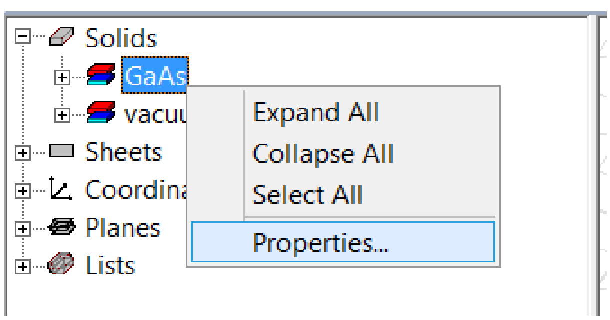

Figure III.4: Changing Material Properties

After the new window have been opened, the Add material option must be selected. The next step is to select the Set Frequency Dependency on the new window. Finally, select Debye Model Input to display the following window.

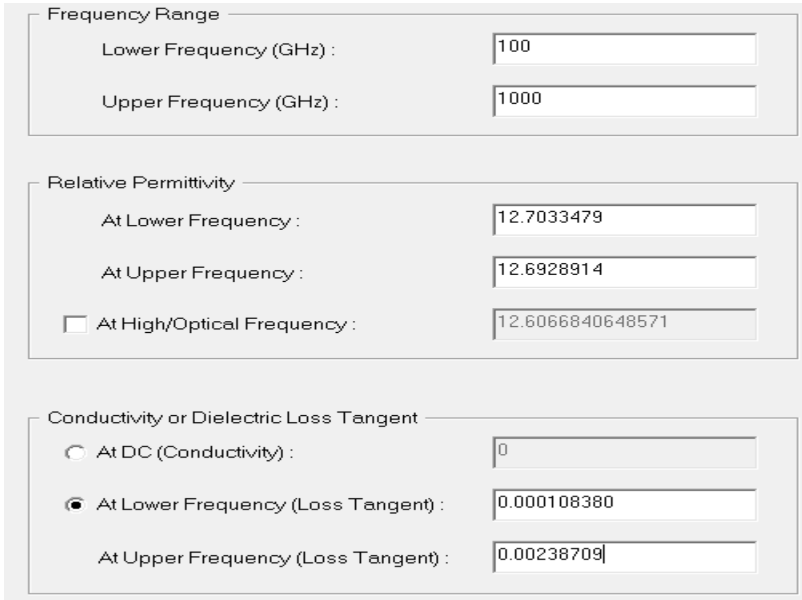

Figure III.5: Debye Model with Custom input [9]

In this window, the properties of the GaAs at the lower and higher frequency range can be inputted to apply the Debye formula. The information for the permittivity of Gallium Arsenide that will be used in this project can be seen in the Table of appendix A [9]**.** After filling up the information and accepting the changes, the model can be analyzed again with the Debye model with custom input instead of the one automatically selected by HFSS. One of the downsides of the Debye model is that it only uses with accuracy the information for the lower and upper frequency range while the rest of the information is obtained through a formula that might not follow the actual data. Thus, since the information for the GaAs substrate over a wide range of frequencies is known, one could come up with a custom formula that is more similar to the actual values of the permittivity. An easy way of obtaining the formula is to plot the permittivity of with respect to frequency in excel and adding a trend line as seen in figure. 6.

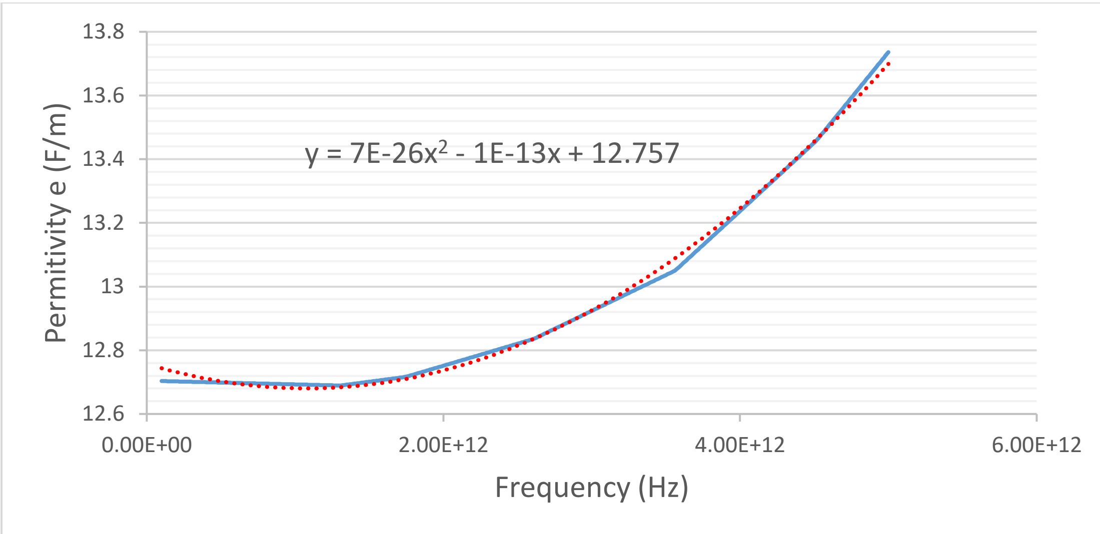

Figure III.6: Trend line for Custom Formula [9]

A similar process can be performed to obtain the loss constant. The final step is to manually input those the formulas in the material editor using the dependent variable Freq instead of X, as shown in Figure 7.

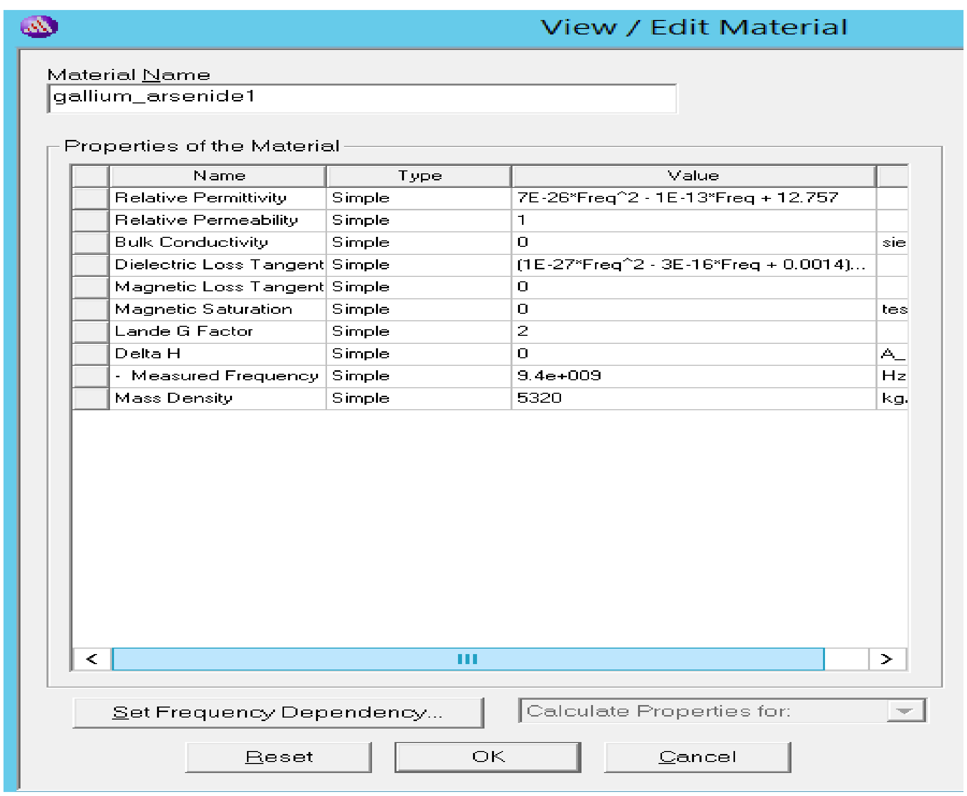

Figure III.7: Manually input Formulas [9]

After accepting all the changes, the model can be analyzed with the custom formula. A comparison between the Debye model that is automatically used by HFSS, the Debye with custom input and the custom formula can be seen in figure. 8.

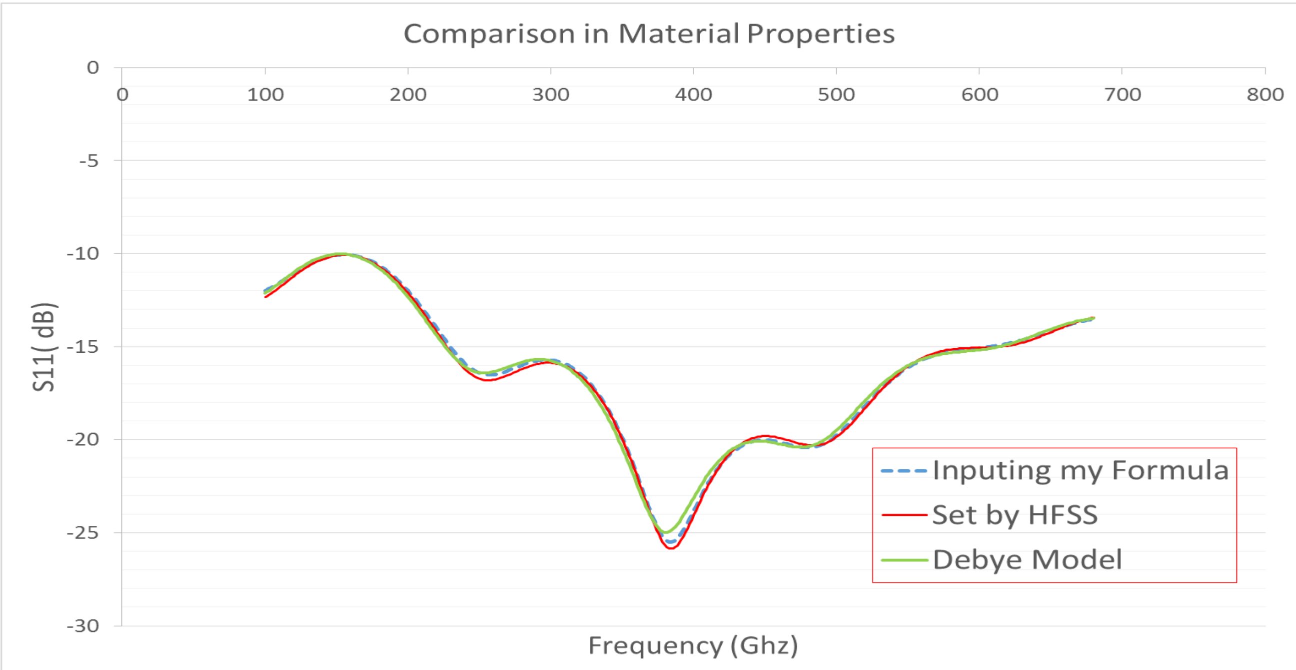

Figure III.8: Comparison in Material Properties

From the graph, it can be seen that the three methods discussed before have very similar results. The main reason for this is because in the frequency range from 0.1 THz to 0.7 THz the permittivity and loss of the dielectric does not change considerably. Thus, the results for each of the formulas discussed before must yield fairly similar results. However, at higher frequencies, the results might not be as similar as in this case. For this reason, it is important to understand that the material properties of the dielectric could have a big effect for a wider range of frequencies.

Another factor that needs to be taken into consideration is the fact that only part of the total antenna is being modeled. Figure 9 shows the upper view of the domains of the antenna.

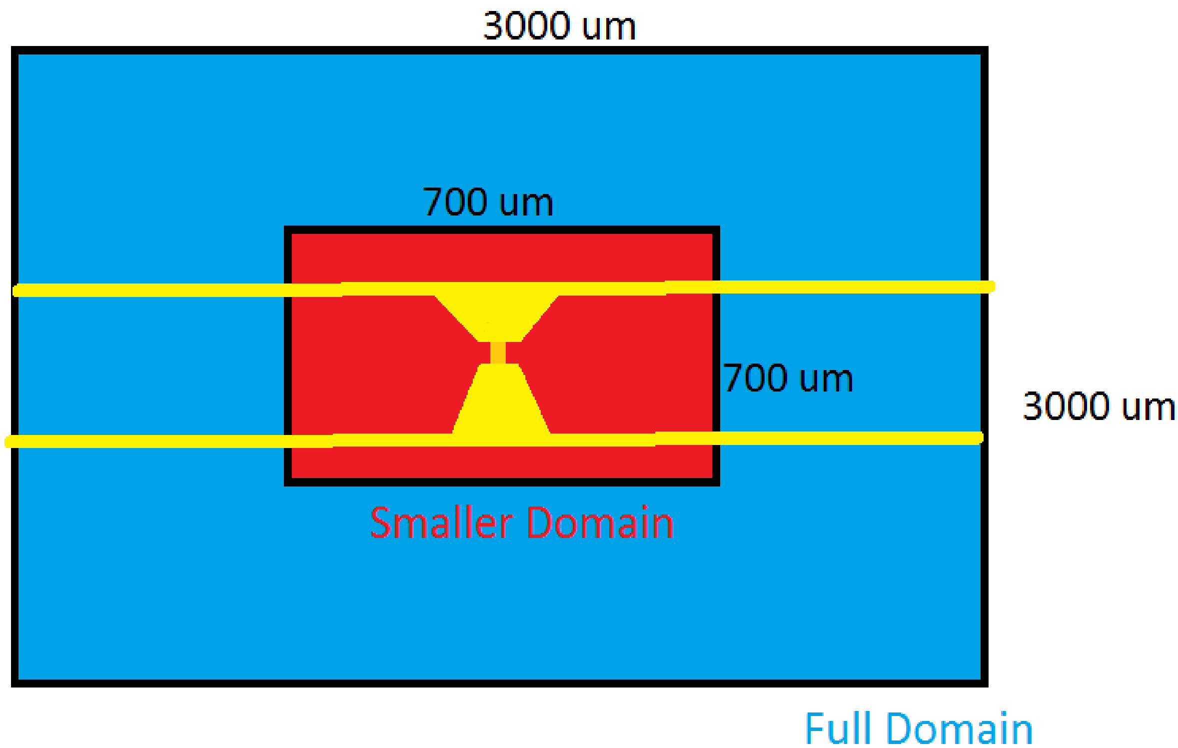

Figure III.9: Full vs Small Domain [3-5]

From the previous figure, the smaller dimension that has been used for the simulations can be seen in red, while the actual dimensions of the physical antenna are shown in blue. The main reason for using a smaller domain instead of the full domain is because it would have taken a lot more of computational power and time to perform the full domain simulations. However, the question of whether reducing the domain has a significant impact on the results must be addressed. In order to do so, the substrate and air box of the model in HFSS was increased to 3000 um and 3000 um in the X and Y direction [3-5]. Moreover, the length of the legs of the antenna were also increased as shown in Figure 9; everything else remained the same. The comparison between the small domain against the full domain can be seen in Figure 10.

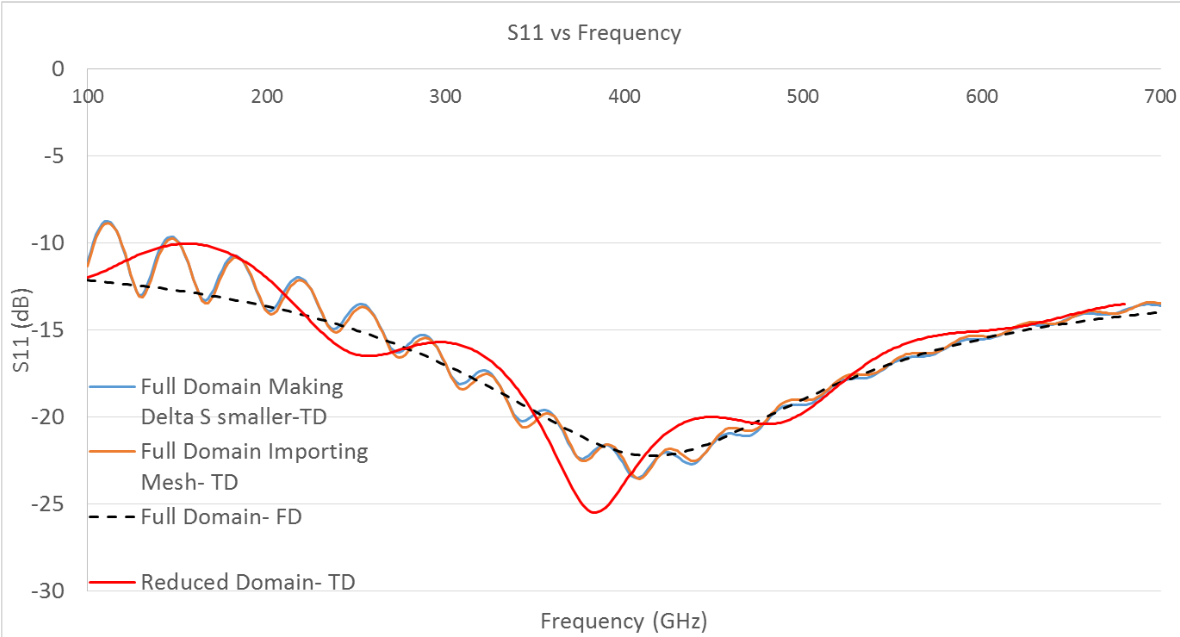

Figure III.10: Comparison Full Domain Vs Small Domain

From the figure, it can be seen that there are some differences between the full and the small domain. One of the differences is that the solution frequency has been shifted from 390 GHz to around 420 GHz. Another difference is that in the frequency domain, the full domain does not have as many oscillations as in the small domain. Moreover, while in the time domain, there are more oscillations in the full domain, it follows the same trend as in the frequency domain for the full antenna. Despite the differences, the magnitude and general trend of both results are similar. In addition, in the following section, it will be seen that although there are some differences in the frequency domain, the results from the time domain are very similar.

D. Importing Current Source and Obtaining Average Electric Field in the Substrate

Knowing that all the considerations have been taken into account, the final step is to use a custom current source to obtain the average electric field in the y-direction somewhere inside the substrate. In order to accomplish this goal, one must first know how to import a current source in HFSS. In the previous simulations, a wave port has been used to excite the port of the antenna to obtain the results shown before. However, the actual physical excitation of the antenna is an optical signal like a laser [3-5]. This laser excites a current on the antenna which can be represented as a current source in the simulation [3-5]. Since the current induced by the laser is already known and available in appendix B**,** it can be imported to HFSS as a dataset [9]. To do so, the first step is to change the solution type from Network Analysis to Composite Excitation. This solution type allows custom dataset to be used as current excitation while the Network Analysis does not [8].

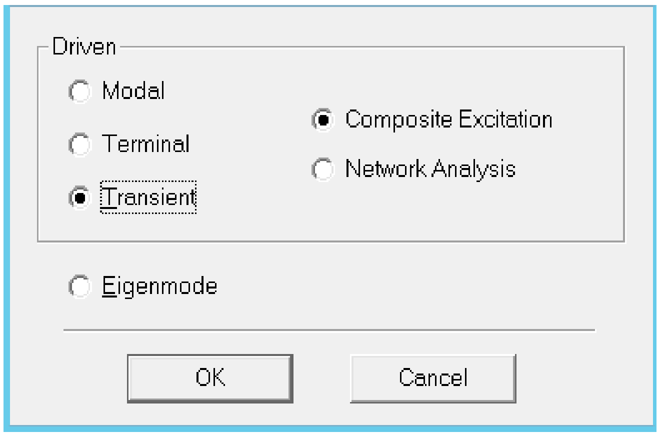

Figure III.11: Solution Type Composited Excitation

In order to import the dataset for the custom current, a file with extension .tab must be created with the information of the custom current. To create this file a text edition like Notepad++ can be used. Open the text editor and copy the information for the current source as shown in the appendix B. Then, the file must be saved with the extension .tab to be recognized by HFSS. Once the file has been saved, right click on a blank space in the project Manager and select Design Datasets. On the new window, the import option must be selected and the .tab file with current information must be selected, as well. The dataset window with the current source selected must looked like Figure. 12.

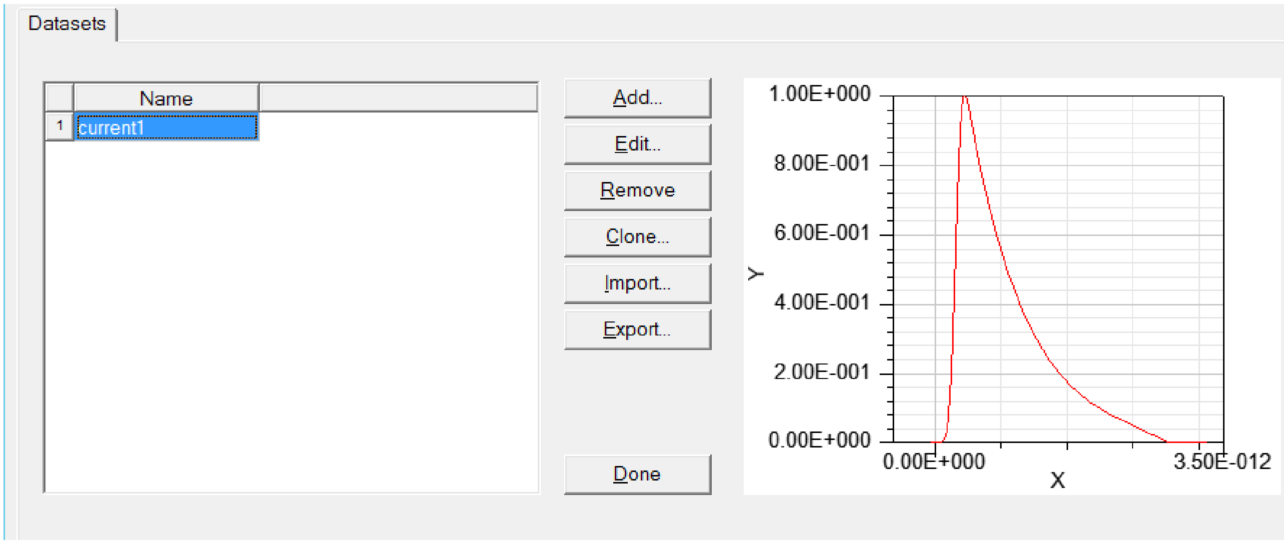

Figure III.12: Importing Custom Current [9]

Once the custom current has been imported, the following step is to delete the available excitations in the project manager. After doing that, right click on the excitation port of the antenna and select Current from the Assign Excitation tab. On the new windows, click on the new line option in the Current Flow direction tab. Then, the direction of the current flow must be assigned by clicking on the lower center of excitation port and then on the upper center as shown in Figure 13.

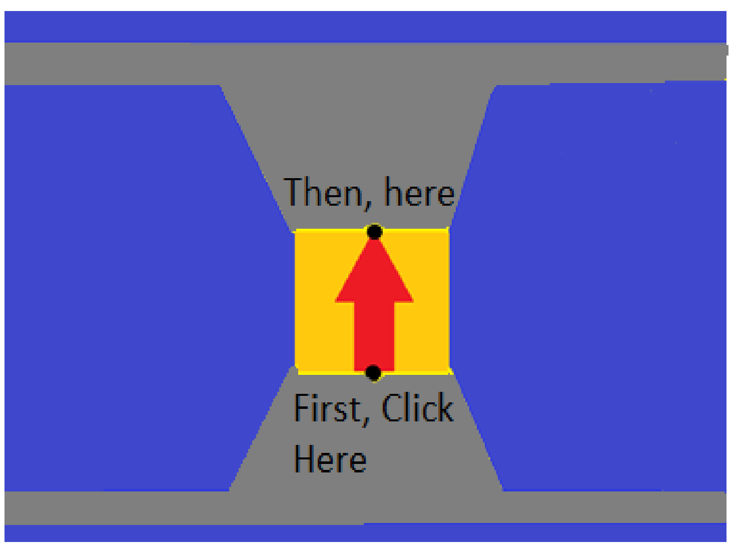

Figure III.13: Flow Direction

In the next window select the Active option and Dataset in the Profile section, as shown in Figure 14. After this, the custom current source excitation has been successfully imported and assigned in the model.

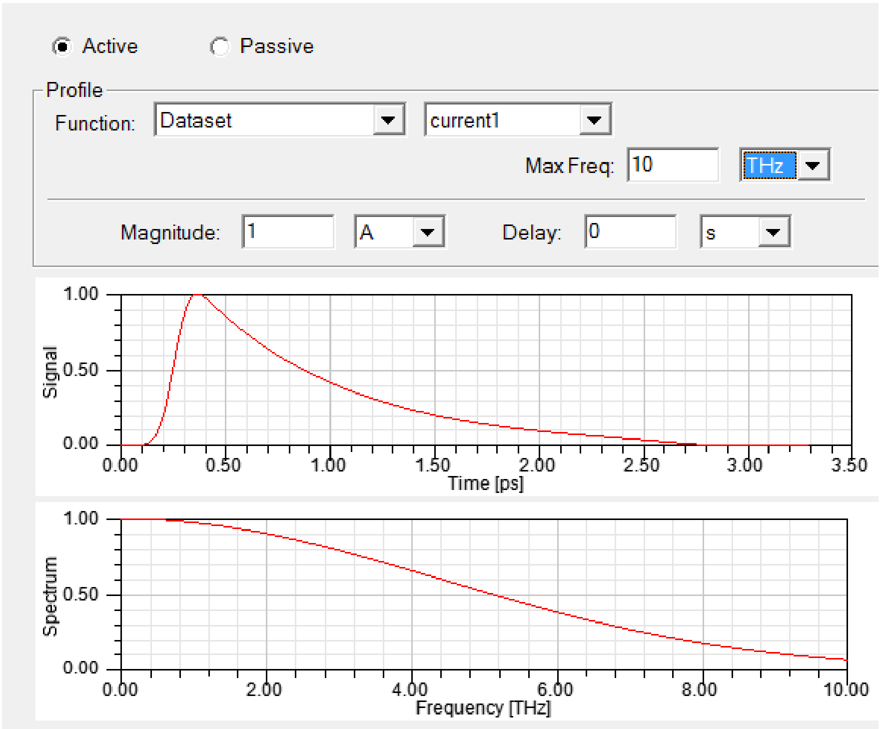

Figure III.14: Custom Current Excitation [9]

The next step is to obtain the electric field in a point in the substrate. In order to do this, the average electric field over a circle inside the GaAs substrate will be obtained. To accomplish this goal, a circle with a radius of 65 um and 250 um under the excitation port must be modeled using the circle option under the Draw tab [3-5]. Moreover, the center of the circle must match exactly with the center of the excitation port [3-5]. Finally, select the circle and click on the Modeler tab at the top of HFSS and go to Create Object List inside the List option. After this, a new solution setup must be created in the project manager. Then, in the Saved Fields tab, select the object list of the circle and assigned the Maximum Number of Samples to be 2000, as shown in Figure 15.

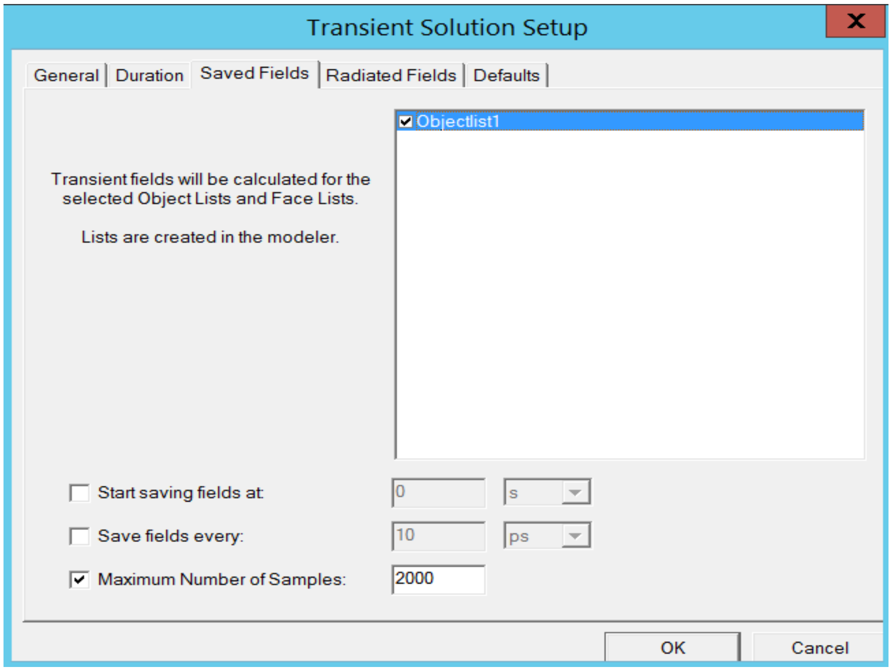

Figure III.15: Saved Fields Option

After that, in the Radiated Fields tab, select the Saved time domain radiated Fields option with a maximum number of samples of 2000, as shown in Figure 16.

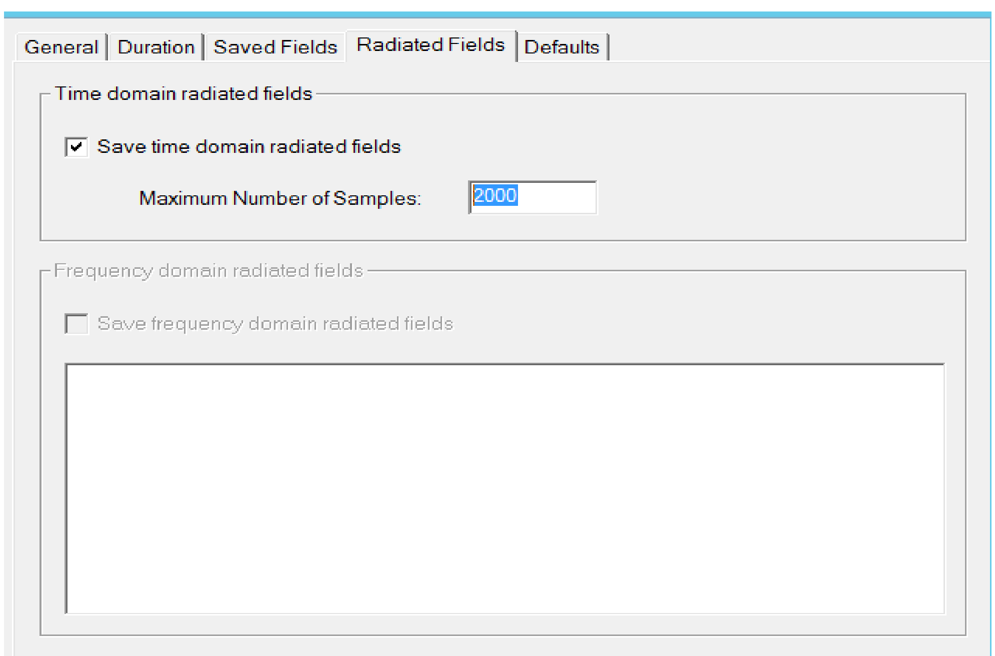

Figure III.16: Radiated Fields Option

These two options allow the fields at the circle to be stored during the simulation [8]. Finally, one of the mesh fixing method can be assigned in the setup up and the simulation can begin. After completing the simulation, the Field Calculator will be used to calculate the average electric field in the y-direction over a circle. To set up the Field Calculator, select the HFSS tab in the top of HFSS and then the calculator option inside the Field section. The field calculator will look like the following Figure.

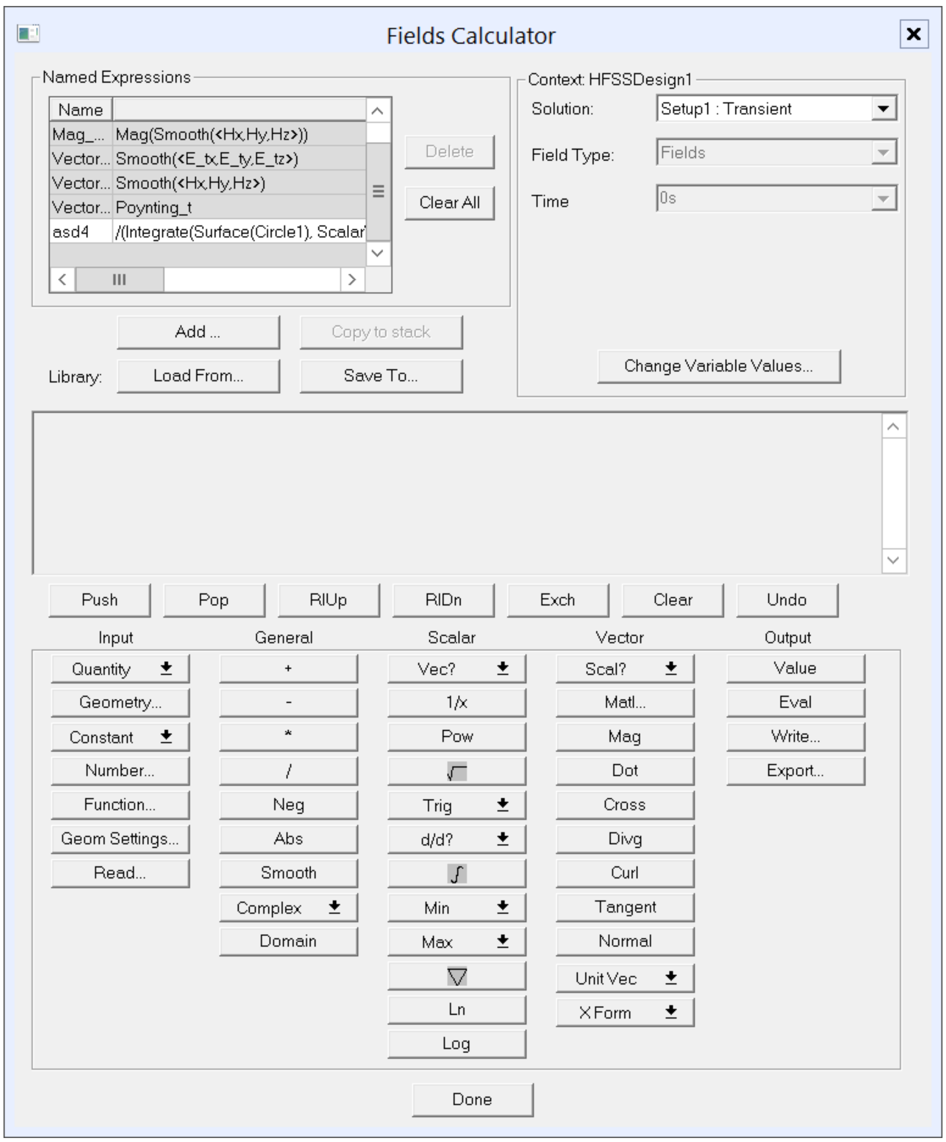

Figure III.17: Field Calculator

The Field Calculator is a useful tool that can be used to perform different operation on the saved fields [8]. To use the Field Calculator, the options at the bottoms are selected in a special order to perform different operations. In order to calculate the average electric field in the y-direction, the instructions shown in Table 1 must be followed.

Table III.1: Field Calculator Average Electric Field in the y-direction [10]

Calculator Operation	Resulting Stack Display
Quantity > E_t	Vec: <E_tx ,E_ty, E_tz>
Scal? > ScalarY	Scl : ScalarY(<E_tx,E_ty,E_tz>)
Geometry> Surface..> {Select the Circle}	Srf : Surface(Circle1) Scl : ScalarY(<E_tx,E_ty,E_tz>)
Value	SclSrf : SurfaceValue(Surface(Circle1), ScalarY(<E_tx,E_ty,E_tz>))
$\int$	Scl : Integrate(Surface(Circle1), ScalarY(<E_tx,E_ty,E_tz>))
Geometry> Surface..> {Select the Circle}	Srf : Surface(Circle1) Scl : Integrate(Surface(Circle1), ScalarY(<E_tx,E_ty,E_tz>))
Unit Vec> Normal	Vec : SurfaceNormal Scl : Integrate(Surface(Circle1), ScalarY(<E_tx,E_ty,E_tz>))
Geometry> Surface..> {Select the Circle}	Srf : Surface(Circle1) Vec : SurfaceNormal Scl : Integrate(Surface(Circle1), ScalarY(<E_tx,E_ty,E_tz>))
Normal	SclSrf : SurfaceValue(Surface(Circle1), Dot(SurfaceNormal, SurfaceNormal)) Scl : Integrate(Surface(Circle1), ScalarY(<E_tx,E_ty,E_tz>))
$\int$	Scl : Integrate(Surface(Circle1), Dot(SurfaceNormal, SurfaceNormal)) Scl : Integrate(Surface(Circle1), ScalarY(<E_tx,E_ty,E_tz>))
/	Scl : /(Integrate(Surface(Circle1), ScalarY(<E_tx,E_ty,E_tz>)), Integrate(Surface(Circle1), Dot(SurfaceNormal, SurfaceNormal)))

After performing the instructions shown in Table 1, the Add option must be selected and a name must be inputted. Then, exit the Field Calculator by selecting Done and right click on

Results on the Project Manager and select Create Field Results and Rectangular Plot. In the Calculator Expressions, select the name of the operation which was recently added as shown in Figure 18.

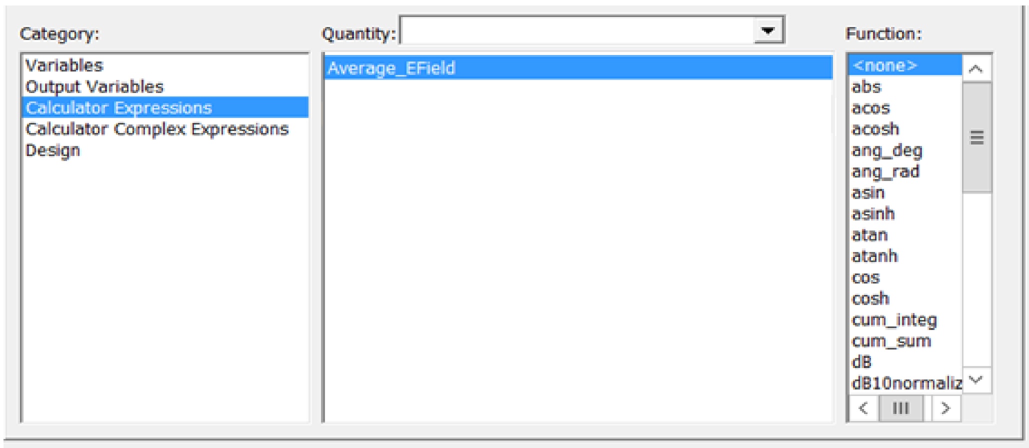

Figure III.18: Plotting Average Electric Field Using Field Calculator Equation

Finally, select New Report and the average electric field in the y-direction over a circle will be plotted. Such plot can be seen in Figure 19.

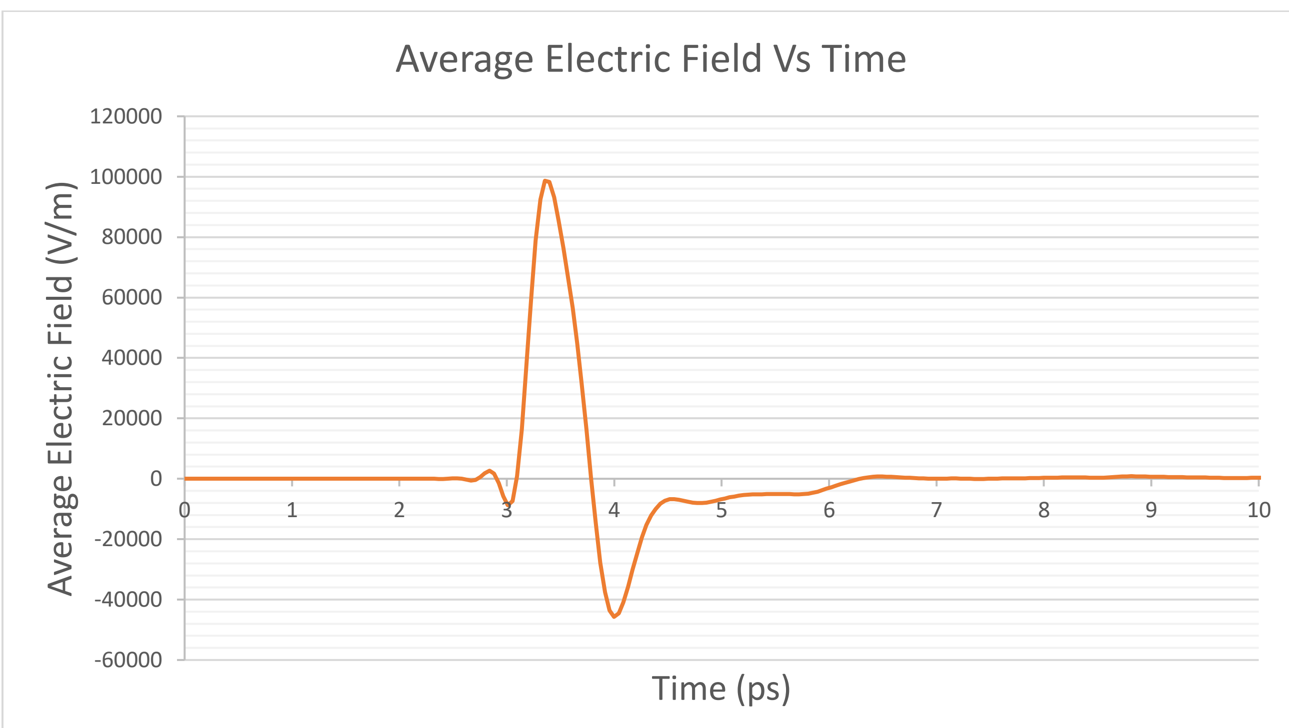

Figure III.19: Average Electric Field in the y- direction

Overall, the shape of the results for the electric field resembles that of a THz pulse, which is the expected result [6]. One of the consideration from section C was whether the fact that the domain of the antenna was reduced affected the results. Applying the same procedure in the full domain of the antenna, the results in Figure 20 are obtained.

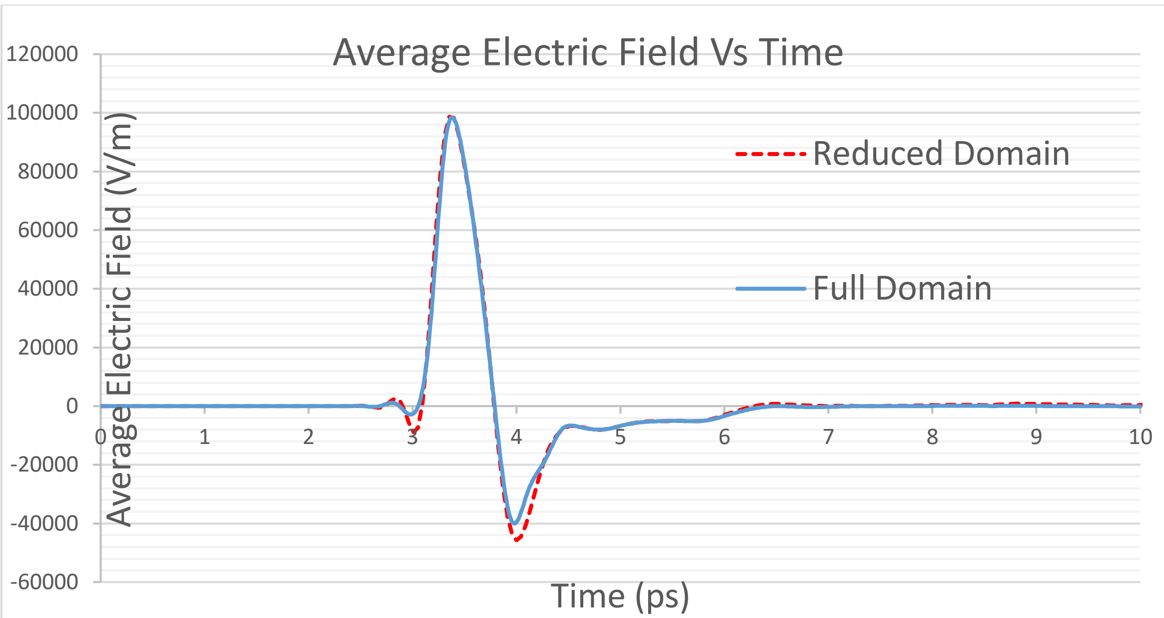

Figure III.20: Comparison Full Domain Vs Reduced Domain Electric Field

From the figure, although there are some small differences, the average electric field in the reduced and the full domain are almost identical. Although the differences in the frequency domain seemed bigger, in the time domain the difference is so small that it is a safe assumption to use the reduced domain instead of the full domain to reduce the time and computational power of the simulation. The final step is to compare the results from COMSOL, conducted by Nathan Burford, with the results obtained here using HFSS. The comparison can be seen in Figure. 21.

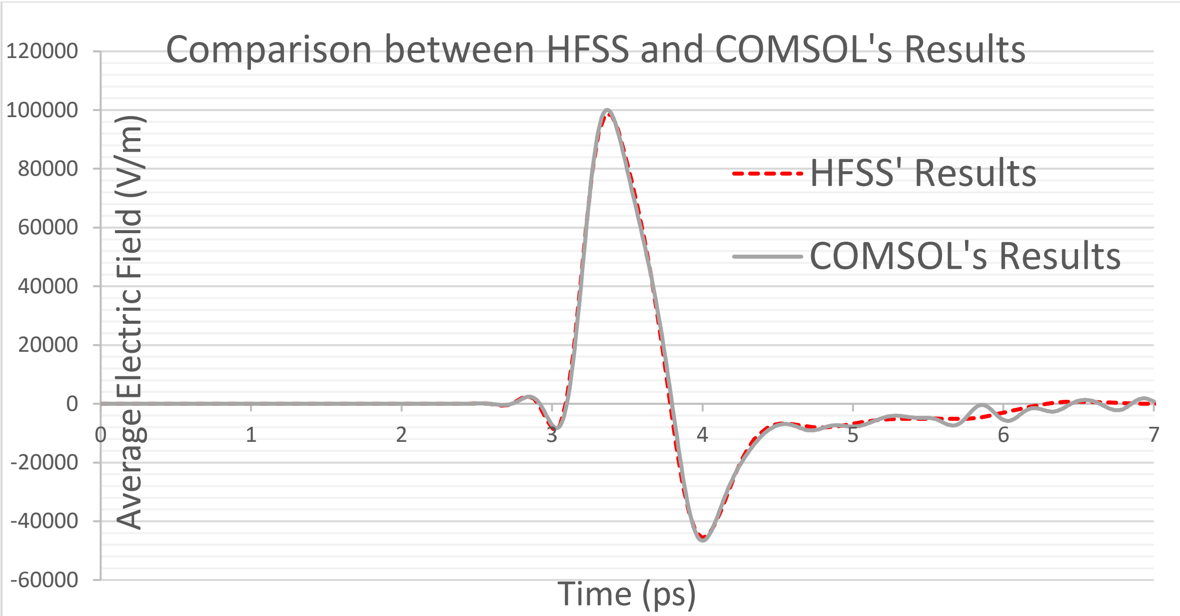

Figure III.21: Comparison between HFSS and COMSOL' Results [3-5]

From the figure, the results for COMSOL and for HFSS are almost identical despite being performed in two different and independent programs. One of the main goals of this project was to develop a procedure to perform a time domain analysis of a photoconductive antenna in order to validate the results from the same antenna in COMSOL. Since the results from Figure 21 proves that both results are almost identical, the goal of this project have been successfully accomplished.

IV. Conclusion

Through this thesis, a detailed guide on how to perform both the frequency and time domains analysis of a THz photoconductive antenna in HFSS has been presented. This guide is intended to fill up the lack of documentation about the transient solver in HFSS for future uses. In Chapter I, the background and motivation for this thesis was presented. In Chapter II, the steps to perform frequency and time domain analysis of the academic paper were discussed. In addition, it was seen that to obtain accurate results, mesh fixing method needed to be implemented in the time domain. Finally, in Chapter III, the THz PCA was simulated to have a custom current source excitation. Using this excitation type, the average electric field in the y-direction of a circle inside the substrate was obtained and compared with the results from COMSOL. It can be concluded that the results from COMSOL and HFSS were in good agreements. Thus, an accurate procedure on how to perform transient analysis of a photoconductive THz antenna was successfully developed.

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Appendix A: GaAs Permittivity [9]

Frequency (THz)	e'	e"						
0.1	12.70335	0.001377	0.53	12.69836	0.015259	0.96	12.69336	0.029135
0.11	12.70323	0.0017	0.54	12.69824	0.015582	0.97	12.69324	0.029458
0.12	12.70312	0.002023	0.55	12.69812	0.015904	0.98	12.69312	0.029781
0.13	12.703	0.002345	0.56	12.69801	0.016227	0.99	12.69301	0.030103
0.14	12.70288	0.002668	0.57	12.69789	0.01655	1	12.69289	0.030426
0.15	12.70277	0.002991	0.58	12.69777	0.016873	1.01	12.69278	0.030749
0.16	12.70265	0.003314	0.59	12.69766	0.017195	1.02	12.69266	0.031071
0.17	12.70254	0.003637	0.6	12.69754	0.017518	1.03	12.69254	0.031394
0.18	12.70242	0.00396	0.61	12.69743	0.017841	1.04	12.69243	0.031717
0.19	12.7023	0.004283	0.62	12.69731	0.018164	1.05	12.69231	0.032039
0.2	12.70219	0.004606	0.63	12.69719	0.018486	1.06	12.69219	0.032362
0.21	12.70207	0.004929	0.64	12.69708	0.018809	1.07	12.69208	0.032684
0.22	12.70196	0.005251	0.65	12.69696	0.019132	1.08	12.69196	0.033007
0.23	12.70184	0.005574	0.66	12.69685	0.019455	1.09	12.69184	0.03333
0.24	12.70172	0.005897	0.67	12.69673	0.019777	1.1	12.69173	0.033652
0.25	12.70161	0.00622	0.68	12.69661	0.0201	1.11	12.69161	0.033975
0.26	12.70149	0.006543	0.69	12.6965	0.020423	1.12	12.6915	0.034297
0.27	12.70138	0.006866	0.7	12.69638	0.020746	1.13	12.69138	0.03462
0.28	12.70126	0.007189	0.71	12.69626	0.021068	1.14	12.69126	0.034943
0.29	12.70114	0.007511	0.72	12.69615	0.021391	1.15	12.69115	0.035265
0.3	12.70103	0.007834	0.73	12.69603	0.021714	1.16	12.69103	0.035588
0.31	12.70091	0.008157	0.74	12.69592	0.022036	1.17	12.69091	0.03591
0.32	12.70079	0.00848	0.75	12.6958	0.022359	1.18	12.6908	0.036233
0.33	12.70068	0.008803	0.76	12.69568	0.022682	1.19	12.69068	0.036556
0.34	12.70056	0.009126	0.77	12.69557	0.023005	1.2	12.69056	0.036887
0.35	12.70045	0.009448	0.78	12.69545	0.023327	1.21	12.69045	0.037227
0.36	12.70033	0.009771	0.79	12.69533	0.02365	1.22	12.69033	0.037567
0.37	12.70021	0.010094	0.8	12.69522	0.023973	1.23	12.69021	0.037907
0.38	12.7001	0.010417	0.81	12.6951	0.024295	1.24	12.6901	0.038247
0.39	12.69998	0.01074	0.82	12.69499	0.024618	1.25	12.68998	0.038587
0.4	12.69987	0.011063	0.83	12.69487	0.024941	1.26	12.68987	0.038927
0.41	12.69975	0.011385	0.84	12.69475	0.025263	1.27	12.68975	0.039267
0.42	12.69963	0.011708	0.85	12.69464	0.025586	1.28	12.68963	0.039607
0.43	12.69952	0.012031	0.86	12.69452	0.025909	1.29	12.68952	0.039946
0.44	12.6994	0.012354	0.87	12.6944	0.026232	1.3	12.6894	0.040286
0.45	12.69928	0.012677	0.88	12.69429	0.026554	1.31	12.6895	0.040627
0.46	12.69917	0.012999	0.89	12.69417	0.026877	1.32	12.69012	0.040968
0.47	12.69905	0.013322	0.9	12.69405	0.0272	1.33	12.69074	0.041309
0.48	12.69894	0.013645	0.91	12.69394	0.027522	1.34	12.69135	0.04165
0.49	12.69882	0.013968	0.92	12.69382	0.027845	1.35	12.69197	0.041991
0.5	12.6987	0.014291	0.93	12.69371	0.028168	1.36	12.69259	0.042332
0.51	12.69859	0.014613	0.94	12.69359	0.02849	1.37	12.69321	0.042673
0.52	12.69847	0.014936	0.95	12.69347	0.028813	1.38	12.69383	0.043014

1.39	12.69445	0.043355	1.87	12.73362	0.0613	2.35	12.79986	0.081866
1.4	12.69507	0.043697	1.88	12.735	0.061688	2.36	12.80124	0.082376
1.41	12.69569	0.044038	1.89	12.73638	0.062075	2.37	12.80262	0.082886
1.45	12.69816	0.045403	1.93	12.74189	0.063687	2.41	12.80815	0.084925
1.46	12.69878	0.045744	1.94	12.74327	0.064112	2.42	12.80953	0.085435
1.47	12.6994	0.046085	1.95	12.74465	0.064537	2.43	12.81091	0.085944
1.48	12.70002	0.046427	1.96	12.74603	0.064962	2.44	12.81229	0.086454
1.49	12.70064	0.046768	1.97	12.74741	0.065387	2.45	12.81367	0.086965
1.5	12.70126	0.047109	1.98	12.74879	0.065812	2.46	12.81505	0.087475
1.51	12.70187	0.047451	1.99	12.75017	0.066238	2.47	12.81644	0.087985
1.52	12.70249	0.047796	2	12.75155	0.066663	2.48	12.81782	0.088495
1.53	12.70311	0.048181	2.01	12.75292	0.067088	2.49	12.8192	0.089005
1.54	12.70373	0.048566	2.02	12.7543	0.067513	2.5	12.82058	0.089516
1.55	12.70435	0.048951	2.03	12.75568	0.067939	2.51	12.82197	0.090026
1.56	12.70497	0.049336	2.04	12.75706	0.068364	2.52	12.82335	0.090536
1.57	12.70559	0.049721	2.05	12.75844	0.06879	2.53	12.82473	0.091047
1.58	12.70621	0.050106	2.06	12.75982	0.069215	2.54	12.82611	0.091557
1.59	12.70682	0.050491	2.07	12.7612	0.069641	2.55	12.8275	0.092068
1.6	12.70744	0.050876	2.08	12.76258	0.070066	2.56	12.82888	0.092579
1.61	12.70806	0.051261	2.09	12.76396	0.070492	2.57	12.83026	0.093089
1.62	12.70868	0.051646	2.1	12.76534	0.070918	2.58	12.83164	0.0936
1.63	12.7093	0.052031	2.11	12.76672	0.071343	2.59	12.83303	0.094111
1.64	12.70992	0.052416	2.12	12.7681	0.071769	2.6	12.83441	0.094622
1.65	12.71054	0.052801	2.13	12.76948	0.072195	2.61	12.83601	0.095134
1.66	12.71116	0.053186	2.14	12.77086	0.072621	2.62	12.83826	0.095648
1.67	12.71178	0.053571	2.15	12.77224	0.073047	2.63	12.8405	0.096162
1.68	12.71239	0.053956	2.16	12.77362	0.073473	2.64	12.84274	0.096676
1.69	12.71301	0.054341	2.17	12.775	0.073899	2.65	12.84498	0.097191
1.7	12.71363	0.054727	2.18	12.77638	0.074325	2.66	12.84723	0.097705
1.71	12.71425	0.055112	2.19	12.77776	0.074751	2.67	12.84947	0.09822
1.72	12.71487	0.055497	2.2	12.77914	0.075177	2.68	12.85171	0.098735
1.73	12.71549	0.055882	2.21	12.78052	0.075603	2.69	12.85396	0.09925
1.74	12.71611	0.056268	2.22	12.7819	0.07603	2.7	12.8562	0.099764
1.75	12.71709	0.056654	2.23	12.78328	0.076456	2.71	12.85844	0.100279
1.76	12.71846	0.057041	2.24	12.78467	0.076882	2.72	12.86069	0.100795
1.77	12.71984	0.057428	2.25	12.78605	0.077309	2.73	12.86293	0.10131
1.78	12.72122	0.057815	2.26	12.78743	0.077735	2.74	12.86517	0.101825
1.79	12.7226	0.058202	2.27	12.78881	0.078161	2.75	12.86742	0.10234
1.8	12.72397	0.058589	2.28	12.79019	0.078588	2.76	12.86966	0.102856
1.81	12.72535	0.058976	2.29	12.79157	0.079014	2.77	12.87191	0.103371
1.82	12.72673	0.059363	2.3	12.79295	0.079441	2.78	12.87415	0.103887
1.83	12.72811	0.059751	2.31	12.79433	0.079868	2.79	12.8764	0.104403
1.84	12.72949	0.060138	2.32	12.79571	0.080338	2.8	12.87864	0.105004
1.85	12.73087	0.060525	2.33	12.79709	0.080847	2.81	12.88089	0.105617
1.86	12.73224	0.060913	2.34	12.79848	0.081357	2.82	12.88313	0.106231

2.83	12.88538	0.106845	3.31	12.99338	0.137171	3.79	13.14727	0.180547
2.84	12.88763	0.107458	3.32	12.99563	0.138064	3.8	13.15154	0.181463
2.85	12.88987	0.108072	3.33	12.99788	0.138958	3.81	13.15581	0.18238
2.89	12.89886	0.110529	3.37	13.0069	0.142534	3.85	13.17289	0.186049
2.9	12.9011	0.111144	3.38	13.00915	0.143429	3.86	13.17716	0.186967
2.91	12.90335	0.111758	3.39	13.0114	0.144323	3.87	13.18143	0.187885
2.92	12.9056	0.112373	3.4	13.01366	0.145218	3.88	13.1857	0.188804
2.93	12.90785	0.112988	3.41	13.01591	0.146113	3.89	13.18998	0.189723
2.94	12.91009	0.113602	3.42	13.01817	0.147008	3.9	13.19425	0.190696
2.95	12.91234	0.114217	3.43	13.02042	0.147903	3.91	13.19852	0.19183
2.96	12.91459	0.114832	3.44	13.02268	0.148799	3.92	13.2028	0.192965
2.97	12.91684	0.115448	3.45	13.02493	0.149694	3.93	13.20707	0.1941
2.98	12.91908	0.116063	3.46	13.02719	0.15059	3.94	13.21135	0.195235
2.99	12.92133	0.116678	3.47	13.02944	0.151486	3.95	13.21562	0.196371
3	12.92358	0.117294	3.48	13.0317	0.152382	3.96	13.2199	0.197507
3.01	12.92583	0.117909	3.49	13.03395	0.153278	3.97	13.22417	0.198643
3.02	12.92808	0.118525	3.5	13.03621	0.154174	3.98	13.22845	0.19978
3.03	12.93033	0.119141	3.51	13.03847	0.155071	3.99	13.23273	0.200917
3.04	12.93258	0.119757	3.52	13.04072	0.155967	4	13.23701	0.202055
3.05	12.93483	0.120373	3.53	13.04298	0.156864	4.01	13.24129	0.203193
3.06	12.93708	0.120989	3.54	13.04524	0.157761	4.02	13.24557	0.204331
3.07	12.93933	0.121605	3.55	13.04749	0.158658	4.03	13.24985	0.205469
3.08	12.94158	0.122222	3.56	13.04975	0.159555	4.04	13.25413	0.206608
3.09	12.94383	0.122838	3.57	13.05356	0.160462	4.05	13.25841	0.207748
3.1	12.94608	0.123455	3.58	13.05782	0.161372	4.06	13.2627	0.208887
3.11	12.94833	0.124071	3.59	13.06207	0.162282	4.07	13.26698	0.210027
3.12	12.95058	0.124688	3.6	13.06632	0.163193	4.08	13.27126	0.211168
3.13	12.95283	0.125305	3.61	13.07058	0.164104	4.09	13.27555	0.212309
3.14	12.95508	0.125922	3.62	13.07483	0.165015	4.1	13.27983	0.21345
3.15	12.95733	0.126539	3.63	13.07909	0.165926	4.11	13.28412	0.214591
3.16	12.95958	0.127156	3.64	13.08335	0.166838	4.12	13.2884	0.215733
3.17	12.96184	0.127774	3.65	13.0876	0.16775	4.13	13.29269	0.216875
3.18	12.96409	0.128391	3.66	13.09186	0.168662	4.14	13.29698	0.218018
3.19	12.96634	0.129009	3.67	13.09612	0.169575	4.15	13.30127	0.219161
3.2	12.96859	0.129626	3.68	13.10038	0.170487	4.16	13.30556	0.220304
3.21	12.97084	0.130244	3.69	13.10464	0.1714	4.17	13.30985	0.221448
3.22	12.9731	0.130862	3.7	13.1089	0.172314	4.18	13.31414	0.222592
3.23	12.97535	0.13148	3.71	13.11316	0.173227	4.19	13.31843	0.223736
3.24	12.9776	0.132098	3.72	13.11742	0.174141	4.2	13.32272	0.224881
3.25	12.97986	0.132716	3.73	13.12169	0.175056	4.21	13.32701	0.226026
3.26	12.98211	0.133334	3.74	13.12595	0.17597	4.22	13.33131	0.227171
3.27	12.98436	0.133953	3.75	13.13021	0.176885	4.23	13.3356	0.228317
3.28	12.98662	0.134571	3.76	13.13448	0.1778	4.24	13.33989	0.229463
3.29	12.98887	0.135384	3.77	13.13874	0.178715	4.25	13.34419	0.230609
3.3	12.99112	0.136277	3.78	13.14301	0.179631	4.26	13.34848	0.231756

4.27	13.35278	0.232903
4.28	13.35708	0.234051
4.29	13.36138	0.235199
4.30	13.36567	0.236347
4.31	13.36997	0.237496
4.32	13.37427	0.238645
4.33	13.37857	0.239794
4.34	13.38287	0.240944
4.35	13.38717	0.242094
4.36	13.39148	0.243244
4.37	13.39577	0.244959
4.38	13.40007	0.246723
4.39	13.40437	0.248488
4.4	13.40867	0.250253
4.41	13.41297	0.252019
4.42	13.41727	0.253786
4.43	13.42157	0.255553
4.44	13.42587	0.25732
4.45	13.43017	0.259088
4.46	13.43447	0.260857
4.47	13.43878	0.262626
4.48	13.44308	0.264396
4.49	13.44739	0.266166
4.5	13.45169	0.267937
4.51	13.456	0.269708
4.52	13.46093	0.271487
4.53	13.46664	0.273274
4.54	13.47235	0.275061
4.55	13.47806	0.276849
4.56	13.48377	0.278638
4.57	13.48948	0.280428
4.58	13.4952	0.282219
4.59	13.50091	0.28401
4.6	13.50663	0.285802
4.61	13.51234	0.287595
4.62	13.51806	0.289388
4.63	13.52378	0.291182
4.64	13.5295	0.292977
4.65	13.53522	0.294773
4.66	13.54095	0.296569
4.67	13.54667	0.298366
4.68	13.5524	0.300164
4.69	13.55812	0.301963
4.7	13.56385	0.303762
4.71	13.56958	0.305562
4.72	13.57531	0.307363
4.73	13.58104	0.309164
4.74	13.58677	0.310966
4.75	13.5925	0.312769
4.76	13.59824	0.314573
4.77	13.60397	0.316378
4.78	13.60971	0.318183
4.79	13.61544	0.319989
4.8	13.62118	0.321795
4.81	13.62692	0.323603
4.82	13.63266	0.325411
4.83	13.6384	0.32722
4.84	13.64415	0.329029
4.85	13.64989	0.33084
4.86	13.65564	0.332651
4.87	13.66138	0.334463
4.88	13.66713	0.336349
4.89	13.67287	0.339064
4.9	13.6786	0.34178
4.91	13.68434	0.344498
4.92	13.69008	0.347216
4.93	13.69582	0.349936
4.94	13.70157	0.352657
4.95	13.70731	0.355379
4.96	13.71305	0.358101
4.97	13.7188	0.360826
4.98	13.72454	0.363551
4.99	13.73029	0.366277
5	13.73604	0.369004

Appendix B: Custom Current Source [9]

"X"	"Y"
-0.048806E-12	-3.00097E-07
0.0062227E-12	0.000572884
0.0634968E-12	0.000557579
0.1072993E-12	0.005248989
0.143255E-12	0.024639726
0.1691267E-12	0.06813662
0.197293E-12	0.1610156
0.2176037E-12	0.25977558
0.2402246E-12	0.4243785
0.254922E-12	0.52490366
0.273028E-12	0.66599226
0.2933683E-12	0.7953225
0.3114314E-12	0.8923194
0.3249528E-12	0.93875897
0.3384628E-12	0.9734409
0.350835E-12	0.9928379
0.3654394E-12	0.998125
0.390139E-12	0.9910637
0.4069684E-12	0.97459835
0.4350111E-12	0.94108117
0.5067952E-12	0.8493512
0.5774653E-12	0.76702785
0.652631E-12	0.6882306
0.765956E-12	0.5853197
0.8871505E-12	0.49122503
1.0689692E-12	0.3777138
1.2137704E-12	0.3071284
1.372054E-12	0.24300617
1.523616E-12	0.19593453
1.66059E-12	0.16062458
1.8739223E-12	0.11765165
2.0962486E-12	0.08467044
2.245594E-12	0.06758174
2.3949394E-12	0.05049304
2.5442848E-12	0.03340434
2.6936302E-12	0.01631564
2.8429756E-12	0
2.992321E-12	0
3.1416664E-12	0
3.2910118E-12	0